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Electromagnetic compatibility tests for the space qualification of the high-voltage system of CALET apparatus

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1 - Introduzione e sommario

1 - Introduction and outline

L'Istituto di Fisica Applicata "Nello Carrara" (IFAC), con supporto finanziario da parte dell'Agenzia Spaziale Italiana ASI¹) e con il coordinamento del dott. Guido Castellini, ha curato lo sviluppo del sistema di alimentazione di alta tensione dell'apparato CALET per la rivelazione dei raggi cosmici a bordo della Stazione Spaziale Internazionale ISS.

In particolare, il personale IFAC che afferisce al Laboratorio di Sicurezza e Compatibilità Elettromagnetica (LabSeCEM) ha effettuato direttamente tutte le prove di interferenza e compatibilità elettromagnetica (EMI/EMC) richieste dallo specifico impiego in ambito spaziale, utilizzando le strutture a disposizione in sede. Infatti il laboratorio LabSeCEM possiede tutta la strumentazione specialistica necessaria ad effettuare tali tipi di prove.

Nelle sezioni seguenti vengono descritte dapprima le principali caratteristiche dell'apparato CALET e in particolare del sistema di alta tensione (sez. 1), quindi il laboratorio LabSeCEM e la sequenza di prove EMI/EMC effettuate (sez. 2). Seguono due appendici che raccolgono informazioni tecniche più dettagliate, sul sistema di alte tensioni (app. 1) e su procedure e risultati delle singole prove EMI/EMC (app. 2).

The Institute of Applied Physics "Nello Carrara" (IFAC), with financial support from Italian Space Agency (ASI) and under coordination of Dr. Guido Castellini, has developed the high-voltage supply system of the CALET apparatus, for the detection of cosmic rays on-board of the International Space Station ISS.

Specifically, the IFAC personnel forming the staff of the Electromagnetic Compatibility and Safety Laboratory (LabSeCEM) directly performed all the electromagnetic interference and compatibility (EMI/EMC) tests required for the employment in space environment, by exploiting the available facilities of the LabSeCEM laboratory, which is equipped with all the necessary and specific instrumentation to perform such tests.

In the following sections we firstly describe the main characteristics of the CALET apparatus and specifically of the high-voltage system (sect. 1), and subsequently the LabSeCEM laboratory and the sequence of EMI/EMC tests performed (sect. 2). Two appendices follow, presenting more detailed technical information on the high-voltage system (app. 1) and on procedures and results of single EMI/EMC tests (app. 2).

2 - L'apparato CALET e il sistema di alta tensione

2 - The CALET apparatus and the high-voltage system

CALET (CALorimetric Electron Telescope) è un apparato per la misura dei raggi cosmici, sviluppato nell'ambito dell'omonima collaborazione scientifica internazionale fra Giappone, Italia e USA, e che sarà lanciato in orbita e installato nel corso del 2014 a bordo della Stazione Spaziale Internazionale (ISS), sul modulo giapponese JEM, con lo scopo principale di misurare i flussi di elettroni e fotoni di alta energia (GeV - TeV), nonché di protoni e nuclei atomici, provenienti dall'esterno del sistema solare.

CALET (CALorimetric Electron Telescope) is an apparatus for measurements of cosmic rays, developed within an international scientific collaboration between Japan, Italy and USA; it will be launched in orbit and installed during 2014 on board of the International Space Station (ISS), on the Japanese module JEM, with the main purpose of measuring the high-energy (GeV - TeV) fluxes of electrons and photons, and also protons and atomic nuclei, originating from outside the solar system.

¹ Contratto IFAC n. 1/046/11/06 (protocollo 3002 del 29/07/2011).

L'apparato CALET (Fig. 1) è principalmente composto da un calorimetro elettromagnetico, integrato da un rivelatore della carica elettrica della particella incidente.

Il calorimetro elettromagnetico occupa un volume approssimativamente cubico di circa 50 cm di lato ed è segmentato orizzontalmente in strati di materiali ad elevata densità (contenenti in particolare tungsteno) e materiali scintillanti; la singola particella carica o fotone di alta energia, attraversando gli strati ad alta densità, produce in genere uno sciame di particelle cariche secondarie, le quali a loro volta interagiscono negli strati scintillanti (fibre scintillanti, tungstato di piombo PWO) generando luce di scintillazione, che viene raccolta mediante vari tipi di rivelatori: tubi fotomoltiplicatori (PMT), fotodiodi (PD) e fotodiodi a valanga (APD). Il rivelatore di carica è a sua volta composto da alcuni strati di scintillatore plastico, che la particella incidente attraversa prima di entrare nel calorimetro.

L'informazione raccolta sull'intensità del segnale di scintillazione e sulla sua distribuzione nei vari strati, permette di determinare la specie e l'energia iniziale della particella primaria incidente.

The CALET apparatus (Fig. 1) is mainly composed of an electromagnetic calorimeter, complemented with a detector of electric charge of the incident particle.

The electromagnetic calorimeter has an approximately cubic size, with about 50 cm side length, and is horizontally segmented in layers of high-density materials (including tungsten) and scintillating materials; the single high-energy charged particle or photon, traversing the high-density layers, typically produces a shower of secondary charged particles, which in turn interact in the scintillating layers (scintillating fibres, lead tungstate PWO) thus generating scintillation light that is collected by different types of detectors: photomultiplier tubes (PMT), photodiodes (PD), avalanche photodiodes (APD). The charge detector is in turn composed of several layers of plastic scintillator, which the incoming particle traverses before entering the calorimeter.

With the collected information on the intensity of the scintillation signal and on its distribution in the various layers, it is possible to determine the species and initial energy of the primary incident particle.

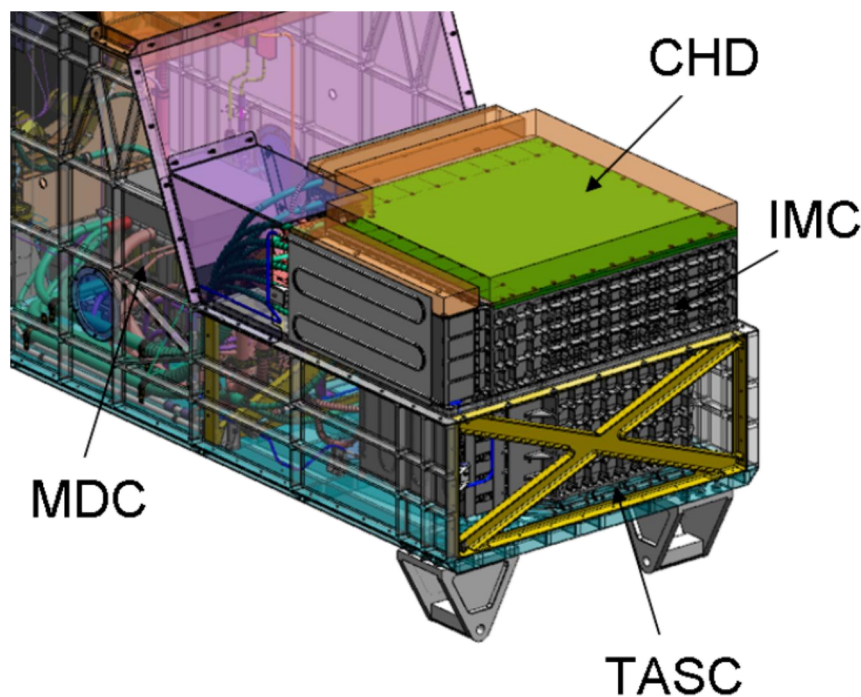


Fig. 1. Disegno dell'apparato CALET, con evidenziati la parte calorimetrica (IMC e TASC), il rivelatore di carica (CHD) e il sistema elettronico di controllo (MDC), presso il quale verrà installato anche il sistema di alte tensioni.

Drawing of the CALET apparatus, highlighting the calorimetric part (IMC and TASC), the charge detector (CHD) and the electronic control system (MDC); the high-voltage system will be installed in the vicinity of the MDC unit.

Il sistema di alte tensioni di CALET (in breve indicato nel seguito come “sistema HV”) ha il compito di generare le alte tensioni (da 500 V a 1000 V) necessarie al funzionamento dei foto-rivelatori di tipo PMT e APD, su un totale di 102 linee indipendenti, indicate di seguito come “linee HV”. Le principali caratteristiche tecniche del sistema HV sono descritte in Appendice 1.

Il sistema HV è stato progettato e realizzato da parte di IFAC, in collaborazione con la ditta SITAEI, che si è occupata principalmente della realizzazione dei circuiti di alta tensione e dell’assemblaggio dell’unità. IFAC ha d’altra parte curato direttamente la progettazione e realizzazione dell’elettronica digitale di controllo e interfaccia e della meccanica di supporto del sistema HV, nonché gli studi di simulazione e le attività di prove in laboratori specializzati, volti a convalidare la compatibilità dell’oggetto con gli stringenti requisiti per l’impiego spaziale, fra cui i seguenti:

- adeguata resistenza della struttura alle sollecitazioni meccaniche incontrate durante la fase di lancio;
- compatibilità dei materiali e dell’elettronica con l’utilizzo nelle condizioni di temperatura e pressione previste in volo orbitale, con prove di qualificazione per temperature comprese fra -20 °C e +65 °C e pressioni inferiori a 10^{-5} mbar;
- compatibilità con gli elevati livelli di radiazione ionizzante presenti in orbita, in particolare per l’elettronica, con qualificazione fino ad almeno 10 krad di dose totale assorbita e immunità per eventi elettrici da singola particella ionizzante (*Single Event Effect* SEE) per tutta la durata della missione (almeno 5 anni);
- qualificazione per interferenza e compatibilità elettromagnetica (EMI/EMC) in funzione delle caratteristiche della stazione spaziale ISS.

The CALET high-voltage system (briefly indicated as “HV system” hereinafter) fulfills the task of generating the high voltages (from 500 V to 1000 V) which are required for the operation of the PMT and APD photo-detectors, with a total of 102 independent lines, indicated as “HV lines” in what follows. The main characteristics of the HV system are described in Appendix 1.

The HV system has been designed and implemented by IFAC, with the contribution of SITAEI company, which mainly worked on the fabrication of the high-voltage circuits and on the assembly of the unit. IFAC in turn directly took care of the design and implementation of the digital electronics, for control and interface of the unit, and of the mechanical structure of the HV system; IFAC personnel also performed simulation studies and test activities at specialized laboratories, to verify the compatibility of the unit with the strict requirements for operation in space environment; among such requirements, it is worth to mention the following ones:

- *adequate stiffness of the structure, with respect to the mechanical stresses encountered during the launch phase;*
- *compatibility of materials and electronics with operation in the foreseen temperature and pressure condition during orbital flight, with qualification tests for temperatures between -20 °C and +65 °C and pressures below 10^{-5} mbar;*
- *compatibility with the high levels of ionizing radiation which are present along the orbit, specifically for electronics, with qualification up to at least 10 krad of total absorbed ionizing dose, and immunity for electrical events caused by single ionizing particle (Single Event Effect SEE) for the whole duration of the mission (at least 5 years);*
- *qualification for electromagnetic interference and compatibility (EMI/EMC) according to the features of the ISS space station.*

Le metodologie di analisi e progettazione, le tecniche di produzione, le procedure e strumentazioni utilizzate per le verifiche in laboratorio, sono state tutte ottimizzate in base ai criteri generali adottati da parte di JAXA e ASI per la preparazione di missioni spaziali, e adattate in funzione delle peculiarità del sistema HV; tutte le attività sono state supervisionate e approvate indipendentemente dai responsabili dei servizi di controllo di produzione e qualità di JAXA e ASI.

Un primo esemplare di sistema HV (denominato “HV Box 001”) è stato fornito a JAXA nel corso del 2012, allo scopo di effettuare studi di caratterizzazione preliminari; l’esemplare “HV Box 002”, che verrà invece integrato con il resto dell’apparato CALET e quindi lanciato in orbita, è stato completato e consegnato a JAXA nel mese di aprile 2013; contestualmente è stata consegnata da parte di IFAC la relativa documentazione di accompagnamento o *Acceptance Data Package* ADP²), da cui sono estratti due rapporti tecnici (illustrati in Appendice 2) che descrivono

² Protocollo IFAC n. 3282 del 21/6/2013.

rispettivamente le procedure e i risultati delle prove di compatibilità elettromagnetica EMI/EMC svolte presso il laboratorio LabSeCEM.

The analysis and design methods, production techniques, procedures and equipment employed for laboratory tests, have all been optimized on the basis of the general criteria adopted by JAXA and ASI for the preparation of space missions, and matched to the peculiar characteristics of the HV system; all the activities have been independently supervised and approved by the officers of the production and quality control services of both JAXA and ASI.

A first specimen of HV system (identified as “HV Box 001”) was delivered to JAXA during 2012, with the purpose of performing preliminary characterization studies; the “HV Box 002” specimen, to be integrated with the rest of the CALET apparatus and launched for flight operation, was completed and delivered to JAXA on April 2013; at the same time, IFAC delivered the required accompanying documentation (Acceptance Data Package ADP), from which two technical reports (illustrated in Appendix 2) have been extracted, for description of the procedures and results of the electromagnetic compatibility EMI/EMC tests performed at the LabSeCEM laboratory.

3 - Il laboratorio LabSeCEM e le prove EMI/EMC

3 - The LabSeCEM laboratory and the EMI/EMC tests

Le prove di interferenza e compatibilità elettromagnetica (EMI/EMC) del sistema HV si sono svolte presso il laboratorio specializzato LabSeCEM presente all'interno dell'istituto IFAC:

- prove di emissione radiata RE e condotta CE, per assicurare che il sistema non emetta radiazione elettromagnetica, o disturbi elettrici condotti attraverso le linee di connessione verso l'esterno (linee di alimentazione in ingresso e digitali), che risultino al di fuori del campo di valori ammessi per non arrecare malfunzionamenti al resto della strumentazione a bordo della ISS;
- prove di suscettività radiata RS e condotta CS, per verificare che applicando al sistema livelli di potenza elettromagnetica radiata o condotta predefiniti (sulla base di quelli presenti sulla ISS), non si osservino scostamenti oltre le tolleranze di progetto ammesse, nella funzionalità e nelle caratteristiche fondamentali del sistema, quali ad esempio l'operatività della parte digitale oppure la linearità e il rumore sulle linee HV.

I livelli di qualificazione necessari, le procedure e la strumentazione impiegate sono stati definiti assieme agli specialisti di JAXA e ASI e da questi approvati, tenendo conto delle tecniche di prove EMI/EMC che costituiscono il riferimento generale per l'ambito ISS⁽³⁾ e armonizzandole con le peculiarità del sistema HV.

The electromagnetic interference and compatibility (EMI/EMC) tests of the HV system have been carried on at the dedicated facility LabSeCEM inside the IFAC premises:

- *tests of radiated emission RE and conducted emission CE, to assure that the system is not generating electromagnetic radiation, or electrical disturbances conducted through the external interface lines (input power and digital lines), resulting in values which are outside the admitted range to avoid malfunctioning in the rest of the equipment on board of the ISS;*
- *tests of radiated susceptibility RS and conducted susceptibility CS, to verify that, when the system is subjected to predefined levels of radiated or conducted electromagnetic power (depending on the values which are present on board of ISS), there are no observations of discrepancies greater than the admitted design tolerances, in the functionality and fundamental characteristics of the system, e.g. the operation of the digital part or the linearity and noise performances of the HV lines.*

The applied qualification levels and the employed procedures and equipment have been defined with the contribution of JAXA and ASI experts, and subsequently approved by them, by considering the EMI/EMC test techniques which form the standard reference for ISS environment⁽⁴⁾, and matching these techniques with the peculiar characteristics of the HV system.

³ Documenti NASA/ESA SSP 30237 rev. F “Space Station Electromagnetic Emission and Susceptibility Requirements” e SSP 30238 rev. E “Space Station Electromagnetic Techniques”.

⁴ NASA/ESA documents SSP 30237 rev. F “Space Station Electromagnetic Emission and Susceptibility Requirements” and SSP 30238 rev. E “Space Station Electromagnetic Techniques”.

Il laboratorio LabSeCEM dispone in particolare di una camera anecoica, assemblata da ETS-Lindgren, delle dimensioni di 7 m · 3 m · 3 m. Le pareti, il soffitto e il pavimento interni della camera sono totalmente ricoperte con piastrelle di ferrite ceramica, che realizzano l'isolamento elettromagnetico con l'ambiente esterno. È inoltre possibile ricoprire le pareti ed il soffitto mediante pannelli adesivi di schiuma assorbente, con strutture piramidali, al fine di estendere l'isolamento ad alte frequenze.

Il livello di isolamento della camera anecoica è appropriato per tutte le tipologie di misure qui discusse, in particolare è stato certificato secondo i parametri internazionali di riferimento da parte della ditta Seibersdorf nel campo di frequenze da 30 MHz a 1 GHz, e qualificato, nella configurazione che fa uso dei pannelli assorbenti, da ETS-Lindgren nel campo da 1 GHz a 18 GHz.

La strumentazione a disposizione include vari modelli di generatori, amplificatori, ricevitori, analizzatori di spettro, oscilloscopi, sonde di corrente, antenne, sonde di campo su diverse bande di frequenza (dalla decina di Hz alla decina di GHz); per la lista dettagliata delle apparecchiature si vedano i rapporti tecnici in Appendice 2. Tutti gli strumenti sono stati calibrati presso ditte specializzate o mediante calibrazione incrociata; dove possibile, la singola misura EMI/EMC è stata replicata con strumenti diversi per verificare la compatibilità delle rispettive calibrazioni.

The LabSeCEM facility is equipped with an anechoic chamber, assembled by ETS-Lindgren company, of size 7 m · 3 m · 3 m. The internal walls, ceiling and floor are completely covered with ceramic ferrite tiles, for electromagnetic insulation from the surrounding environment. It is also possible to cover the walls and ceiling by means of adhesive panels made of absorbing foam, with pyramidal structures, to extend the insulation toward higher frequencies.

The LabSeCEM anechoic chamber guarantees an insulation level which is adequate for all the specific tests here discussed; in particular, the insulation has been certified by Seibersdorf company, according to the international reference standards, in the frequency range from 30 MHz to 1 GHz, and qualified by ETS-Lindgren in the configuration obtained by installing the absorbing panels, for the range 1 GHz - 18 GHz.

The available equipment includes several models of generators, amplifiers, receivers, spectrum analyzers, oscilloscopes, current probes, antennae, field probes over different frequency bands (from tens of Hz to tens of GHz); see technical reports in Appendix 2 for the detailed list of devices. All instruments have been calibrated by specialized companies or by means of cross-calibration; where possible, the single EMI/EMC measurement has been repeated with different devices, to verify the compatibility of the calibrations.

Durante le prove il sistema HV è stato posto all'interno della camera anecoica e collegato, quando previsto nella procedura, a:

- alimentatori in continua per la generazione delle tensioni in ingresso richieste (28V, 5.6V, 3.5V);
- un sistema elettronico (sviluppato da IFAC) che replica le funzionalità dell'unità MDC di controllo dell'apparato CALET, in modo da poter inviare comandi al sistema HV attraverso l'interfaccia digitale, e verificare le risposte generate da questo;
- un sistema di carichi resistivi sulle linee HV, in modo da riprodurre la presenza dei collegamenti ai canali PMT e APD, come avviene nella configurazione tipica di lavoro dell'apparato CALET.

Le varie prove EMI/EMC effettuate sono identificate, nella documentazione di riferimento sopra citata, con le seguenti sigle: CE01, CE03, CE07; CS01, CS02, CS06; RE02; RS02, RS03. La descrizione dettagliata delle singole prove è riportata in Appendice 2; di seguito ne vengono illustrate soltanto le caratteristiche essenziali.

During tests the HV system has been placed inside the anechoic chamber and, when required in the procedure, it has been connected to:

- *DC power supplies for generation of the needed input voltages (28V, 5.6V, 3.5V);*
- *an electronic system (developed by IFAC) which reproduces the functionality of the MDC unit for the control of the CALET apparatus, to be able to send commands to the HV system via the digital interface, and check the corresponding responses;*
- *an array of resistive loads on the HV lines, in such a way to reproduce the presence of connections with the PMT and APD channels, as in the typical operating configuration of the CALET apparatus.*

The different EMI/EMC tests, which have been performed, are identified with the following codes in the above cited reference documentation: CE01, CE03, CE07; CS01, CS02, CS06; RE02; RS02, RS03. The detailed description of each single test is reported in Appendix 2; in what follows, only the essential characteristics are illustrated.

Le prove di emissione condotta CE01 e CE03 mirano a verificare che, su ciascuna linea di alimentazione in ingresso (28V, 5.6V, 3.5V), l'unità inietti uno spettro di potenza elettromagnetica nei limiti prefissati, misurato mediante sonda magnetica di corrente, nel campo di frequenza da 30 Hz a 50 MHz.

La prova di emissione condotta CE07 consiste nella misura della forma d'onda in tensione osservata sui terminali di ingresso delle linee di alimentazione, quando le corrispondenti tensioni vengono accese o spente, per verificare che la forma d'onda rientri nel profilo temporale ammesso.

La prova di emissione radiata RE02 ha lo scopo di verificare che il sistema HV emetta uno spettro di radiazione elettromagnetica nei limiti prefissati, nel campo di frequenze da 14 kHz a 16 GHz.

The CE01 and CE03 conducted emission tests are aimed at verifying that, for each input power line (28V, 5.6V, 3.5V), the unit injects an electromagnetic power spectrum contained within the predefined limits, when measured through a magnetic current probe, in the frequency range 30 Hz - 50 MHz.

The CE07 conducted emission test consists in the measurement of the voltage waveform observed at the input terminals of the power lines, when the corresponding voltages are powered on and off, to check that the waveform falls within the admitted time profile.

The RS02 radiated emission test is conceived to verify that the HV system generates an electromagnetic radiation spectrum which is inside the predefined limits, in the frequency range from 14 kHz to 16 GHz.

Le prove di suscettività condotta e radiata CS e RS mirano a verificare che l'unità non mostri deviazioni dal regolare funzionamento, in presenza di potenza elettromagnetica iniettata nel sistema HV attraverso le linee di alimentazione o digitali, o irradiata mediante antenne posizionate nelle vicinanze; le principali verifiche effettuate sono le seguenti:

- regolarità delle correnti assorbite sulle linee di alimentazione (28V, 5.6V, 3.5V);
- corretta funzionalità della parte digitale di controllo e assenza di errori di trasmissione nell'interfaccia digitale verso MDC;
- assenza di allarmi (sovratensioni, sovracorrenti ecc.);
- linearità e rumore del segnale di alta tensione sulle linee HV.

Nello specifico, le prove di suscettività condotta CS01 e CS02 prevedono di applicare su ciascuna linea di alimentazione uno spettro di segnale predefinito, nel campo di frequenze da 30 Hz a 50 MHz, mediante accoppiamento induttivo e capacitivo rispettivamente.

Le prove CS06 e RS02 richiedono di applicare impulsi ripetuti della durata di 10 μ s e 150 ns, mediante accoppiamento capacitivo su singola linea di alimentazione (CS06) e induttivo sull'insieme delle linee digitali (RS02).

Infine la prova di suscettività radiata RS03 prevede di applicare uno spettro di segnale prefissato, tramite antenne, nel campo di frequenze da 14 kHz a 15 GHz.

The susceptibility tests, CS and RS, are aimed at verifying that the unit does not show deviations from normal operation, when electromagnetic power is injected in the HV system through the power or digital lines, or radiated from nearby antennae; the main performed checks are as follows:

- *absorbed currents on the power lines (28V, 5.6V, 3.5V);*
- *nominal operation of the digital control part and absence of transmission errors in the digital interface towards MDC;*
- *absence of alarms (overvoltages, overcurrents etc.);*
- *linearity and noise of the high-voltage signals on the HV lines.*

Specifically, in the CS01 and CS02 conducted susceptibility tests, a predefined signal spectrum is applied on each power line, in the frequency range 30 Hz - 50 MHz, by means of inductive and capacitive coupling respectively.

The CS06 e RS02 tests require to apply repeated pulses of 10 μ s and 150 ns duration, through capacitive coupling on single power lines (CS06) and inductive coupling on the whole bunch of digital lines (RS02).

Finally, in the RS03 radiated susceptibility test, a predefined signal spectrum is applied by means of antennae, in the frequency range from 14 kHz to 15 GHz.

I risultati delle prove EMI/EMC effettuate sono descritti in Appendice 2, dove sono mostrate anche alcune fotografie delle varie configurazioni sperimentali utilizzate.

Le prove hanno dato nel complesso esito positivo, con due tipologie di non-conformità che JAXA e ASI hanno giudicato non avere impatto significativo per l'impiego del sistema HV a bordo della stazione spaziale ISS, con conseguente accettazione da parte di JAXA e ASI della qualificazione così ottenuta presso il laboratorio LabSeCEM.

The results of performed EMI/EMC tests are described in Appendix 2, where several photographs are also shown of the various employed experimental configurations.

The tests gave an overall positive result, apart from two types of non-conformities that have been judged by JAXA and ASI not to have significant impact on the employment of the HV system on board of the ISS space station, with consequent acceptance by JAXA and ASI of the qualification thus obtained at LabSeCEM laboratory.

Appendice 1: caratteristiche del sistema HV di CALET

Appendix 1: characteristics of the CALET HV system

Il sistema HV di CALET (si vedano Fig. 2 e Fig. 3) è composto da una struttura portante in alluminio approssimativamente cubica, con dimensioni dei lati 29 cm · 24 cm · 24 cm, in cui sono alloggiati:

- 80 moduli che costituiscono la “sezione PMT” e forniscono altrettante linee di alta tensione negativa (regolabile da 0 a -900 V) per i foto-rivelatori PMT di CALET;
- 22 moduli che formano la “sezione APD”, con altrettante linee regolabili da 0 a -500 V per i foto-rivelatori di tipo APD;
- le corrispondenti schede elettroniche (denominate PHCB e AHCB) di controllo e interfaccia con l’unità MDC che realizza il controllo dell’apparato CALET.

Il peso del sistema HV è di circa 14 kg; la potenza assorbita è 22 W in configurazione operativa tipica.

The CALET HV system (see Fig. 2 and Fig. 3) is composed of an aluminium support structure, approximately cubic, with side lengths 29 cm · 24 cm · 24 cm, housing:

- 80 modules forming the “PMT section” and delivering a corresponding number of negative high-voltage lines (voltage can be set from 0 to -900 V) for the PMT photo-detectors of CALET system;
- 22 modules forming the “APD section”, with a corresponding number of lines, which can be set from 0 to -500 V, for the APD photo-detectors;
- the related electronic boards (named PHCB and AHCB) for control and interface with the MDC unit managing the operation of the CALET apparatus.

The HV system weights about 14 kg; its power consumption is 22 W in the typical operating configuration.

La sezione PMT e la sezione APD sono fisicamente suddivise in due metà identiche (Fig. 4), con le singole parti di ciascuna metà raddoppiate per ridondanza: le parti raddoppiate sono identificate come *hot* (normalmente tenuta accesa) e *cold* (normalmente tenuta spenta e usata in sostituzione della parte *hot* in caso di guasto irreparabile di quest’ultima). Lo schema a blocchi di metà sezione PMT è riportato in Fig. 5, quello di metà sezione APD in Fig. 6.

Sul lato frontale dell’unità sono presenti 102 connettori coassiali miniaturizzati per le altrettante linee di alta tensione in uscita (“linee HV”), mentre sul retro sono posizionati i connettori di tipo micro-D, utilizzati per le tensioni di alimentazione in ingresso e per i segnali digitali.

Il sistema HV è predisposto per interfacciarsi con l’unità MDC di controllo dell’apparato CALET e richiede tre diverse tensioni di alimentazione (+28 V, +5.6 V, +3.5 V), mentre l’interfaccia digitale, per dati e comandi, è realizzata mediante collegamenti seriali bidirezionali di tipo LVDS, con velocità di trasmissione tipica di 1 Mbps.

Le linee HV sono state progettate e caratterizzate per avere una linearità migliore del 3% e un rumore (*ripple*) inferiore a 150 mV picco-picco.

The PMT and APD sections are physically divided into two identical halves (Fig. 4); for each half, the single parts are replicated for redundancy: the doubled parts are identified as hot (normally powered-on) and cold (normally kept powered-off and used for substitution of the hot part in the case of unrecoverable damage of that one). The block scheme for half PMT section is illustrated in Fig. 5, while for half APD section is reported in Fig. 6.

On the front side of the unit, 102 miniaturized coaxial connectors are installed, for the corresponding high-voltage output lines (“HV lines”), while on the rear side micro-D connectors are positioned, which are employed for input power lines and digital signals.

The HV system is designed to be interfaced with the MDC unit managing the operation of the CALET apparatus, and it requires three different power voltages (+28 V, +5.6 V, +3.5 V), while the digital interface, for data and commands, is implemented with LVDS bidirectional serial links, with typical transmission rate of 1 Mbps.

The HV lines have been designed and characterized for a linearity better than 3% and a noise (ripple) less than 150 mV peak-to-peak.



Fig. 4. Il sistema HV prima dell'assemblaggio finale, con le due metà separate.

The HV system before the final assembly, with the two halves separated.

La struttura logica interna, realizzata su dispositivi di logica programmabile FPGA a bordo delle schede PHCB e AHCB, prevede un insieme di comandi elementari che permettono le seguenti operazioni:

- accendere/spengere una singola linea HV o gruppi di linee HV;
- regolare la tensione in uscita per ciascuna linea HV, con una risoluzione dello 0.1% su tutto il campo dinamico;
- monitorare in tempo reale il valore delle tensioni in uscita per la sezione APD;
- memorizzare e rileggere la configurazione delle singole linee;
- rilevare in tempo reale la presenza di condizioni anomale, quali sovratensione o sovracorrente sui moduli di alta tensione, oppure SEE dovuti a singola particella ionizzante;
- effettuare all'accensione del sistema, e senza necessità di ricevere alcun comando, la configurazione automatica delle varie linee HV, secondo un criterio prestabilito in base alle caratteristiche dei canali PMT o APD del calorimetro di CALET, connessi a ciascuna linea HV.

The internal logic structure has been implemented by means of FPGA programmable logic devices on the PHCB and AHCB boards; it includes a set of elementary commands, which allow the following tasks:

- *to power on/off a single HV line or groups of HV lines;*
- *to set the output voltage for each HV line, with 0.1% resolution over the whole dynamic range;*
- *the real-time monitoring of the output voltage values for the APD section;*
- *to save and read the configuration of single lines;*
- *the real-time detection of anomalous conditions, such as overvoltage or overcurrent in the high-voltage modules, or SEE caused by single ionizing particle;*
- *at system power-on, to automatically configure the different HV lines, without needing to receive any external command, according to a scheme which has been defined on the basis of the characteristics of the PMT or APD channels which are connected to each HV line.*

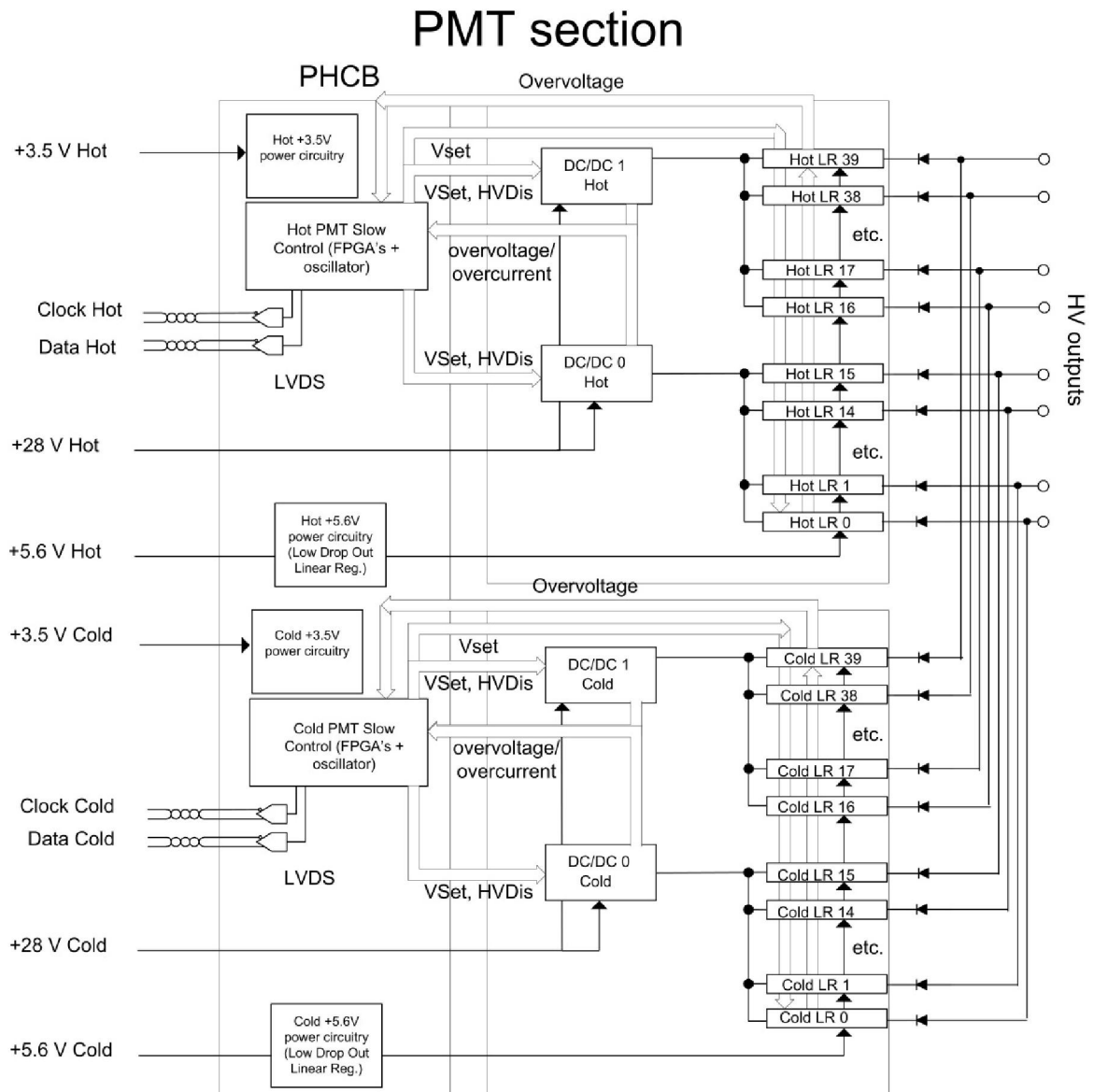


Fig. 5. Schema della sezione PMT per una metà del sistema HV.

Scheme of the PMT section for half HV system.

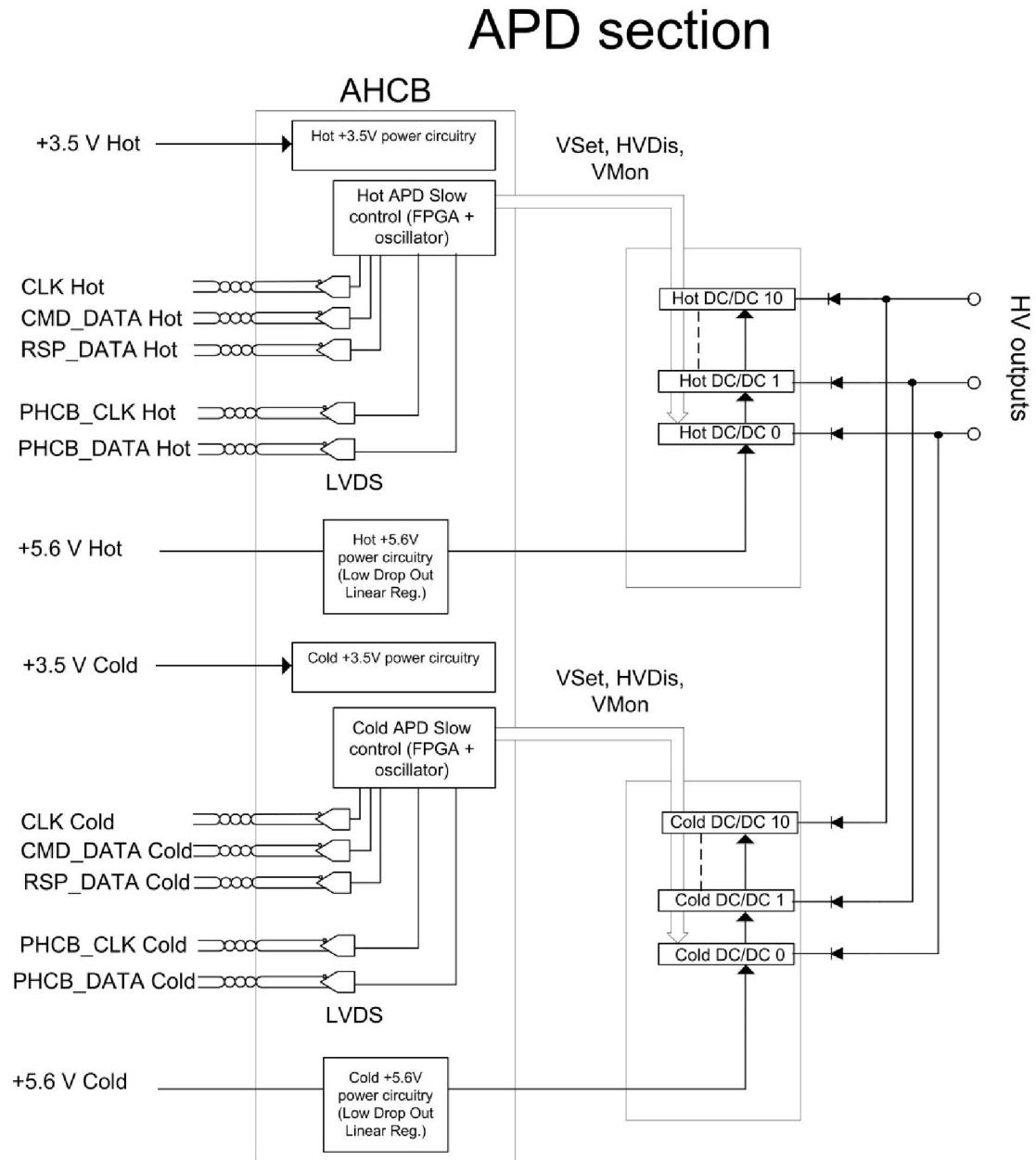


Fig. 6. Schema della sezione APD per una metà del sistema HV.

Scheme of the APD section for half HV system.

Appendice 2: rapporti tecnici delle prove EMI/EMC.

Appendix 2: technical reports of EMI/EMC tests.

Questa appendice presenta la sintesi dei seguenti documenti (in inglese):

- IFAC-CALET-T-045 rev. B. Procedure e strumentazione per le prove EMI/EMC su sistema HV (“HV Box 002”);
- IFAC-CALET-T-078 rev. B. Rapporto delle prove EMI/EMC effettuate su sistema HV (“HV Box 002”).

In this appendix the synthesis of the following documents is presented:

- *IFAC-CALET-T-045 rev. B. Procedures and equipment for the EMI/EMC tests of HV system (“HV Box 002”);*
- *IFAC-CALET-T-078 rev. B. Report of performed EMI/EMC tests on HV system (“HV Box 002”).*

1. Introduction

This document illustrates the procedure, equipment and results for EMI/EMC tests of the CALET HV Box unit 002, performed during final test flow: CE01; CE03; CE07; CS01, CS02, CS06; RE02; RS02, RS03.

The EMI/EMC test is aimed at verifying the following main aspects:

- that the conducted emission characteristics on input power lines are compatible with limits according to tests CE01, CE03, CE07;
- the unit susceptibility to applied conducted power according to tests CS01, CS02, CS06;
- that the radiated emission characteristics are compatible with limits according to test RE02;
- the unit susceptibility to applied radiated power according to tests RS02, RS03.

Detailed requirements to be satisfied for the successful completion of the EMI/EMC test are specified in what follows.

As shown in the test results below, and with the exception of two minor non-conformities, the test has been successfully completed and the overall positive outcome have been accepted by ASI and JAXA.

2. References

2.1. SSP30237 Rev. F. Space Station Electromagnetic Emission and Susceptibility Requirements. 17 May 2001. NASDA, ESA, ASI, CSA, NASA.

2.2. SSP30238 Rev. E. Space Station Electromagnetic Techniques. 31 July 2002. NASDA, ESA, ASI, CSA, NASA.

3. General test configuration

The test is performed at IFAC LabSeCEM laboratory; measurement conditions are applied as specified in [2.1] and [2.2] (when applicable). The following environment conditions are satisfied:

- Temperature: 15 to 35 °C.
- Pressure: 610 to 780 mm Hg.
- Relative Humidity: 20 to 80 % of saturation.

Test equipment and HV Box are placed over a copper ground plane. All metal cases of test equipment and HV Box are connected to the common ground plane, which in turn is connected to the shielded enclosure (anechoic chamber). All power RTN lines of HV Box are kept floating with respect to the ground plane. Cable bundles are

separated by at least 5 cm from each other. Cables are placed at least 5 cm above the ground plane. Cables are placed within 10 cm of the lateral edge of the ground plane.

Prior to performing tests, the measuring equipment is kept powered-on for a period of time of 1 hour. For each command sent to HV Box, the MDC emulator automatically checks all the response data bits generated by the HV Box, for consistency with the expected response data (in particular, it checks that all “command error” bits are set to 0).

4. CE01 and CE03 tests

4.1. Configuration (CE01, CE03 tests)

The test configuration is shown in Fig. 7. The test is performed on each power input line. Power is brought to these inputs by means of 1.5 m long, AWG 24, non-twisted, non-shielded pairs of wires. During measurement, the current probe surrounds both the V_{test} and $V_{\text{test_RTN}}$ wires (common mode current measurement).

Different combinations of interference analyzers and current probes are employed for the various tests. The response of the measuring system to conducted emission levels, for the various analyzer/probe configurations employed has been calibrated:

- (A) either by injecting a known current (from a calibrated generator) into the current probe and by recording the read-out of the analyzer in the range of frequencies for which the specified analyzer/probe configuration is employed for the current test;
- (B) or by referring to the analyzer/probe specifications and validating these specifications by cross-checking with a different analyzer/probe configuration, previously calibrated by method (A).

The set-up used for low frequencies ($f < 10$ kHz) is based on a digital oscilloscope. The oscilloscope read-out is analyzed by Fourier analysis with MATLAB tool, to identify possible peaks emerging from the ambient noise.

At high frequencies ($f > 10$ kHz), a spectrum analyzer or EMI test receiver is employed; during the measurement, the instrument is set in peak mode. Tab. 1 reports the applied 3 dB filter bandwidth, total sweep time, and number of sweeps which are averaged to give the final result, for each frequency interval.

Tab. 1: configuration of interference analyzer ($f > 10$ kHz) for CE01 and CE03 test.

frequency range	3 dB filter bandwidth	total sweep time (s)	number of sweeps (averaged)
10 kHz - 150 kHz	1 kHz	200	2
150 kHz - 30 MHz	10 kHz	200	2
30 MHz - 50 MHz	10 kHz	100	2

During test CE01 the following analyzer/probe configuration has been used:

- **C₁.** A₁: oscilloscope Lecroy Waverunner 6100A. Bandwidth set to 20 MHz. Resolution set to 50 MSa/s.
P₁: LEM PR30 AC/DC oscilloscope probe.

During test CE03 the following analyzer/probe configurations have been used (data collected with different configurations were consistent with each other):

- **C₁.** See above.
- **C₂.** A₂: Rode&Schwarz FSL6 Spectrum Analyzer. P₂: ETS 935511-1.
- **C₃.** A₃: Rode&Schwarz ESPI7 EMI Test Receiver. P₄: ETS 91550-2L.

Other employed equipment.

- Power supplies, current meters:
 - Agilent U8032A. S/N MY52180017. Calibration expiry date 2013-05-03.
 - TTI QL355T. S.N. 346658. Current meter cross-calibrated with Agilent U8032A.
- Calibrated generator: Marconi Instruments, Digital and Vector Signal Generator 2051, 10 kHz - 2.7 GHz. S/N 119737/087. Calibration expiry date: 2013-03-21.
- Isolation transformer: K-FACTOR, Three Phase Isolation Transformer, 16 kVA, primary 400 V 23 A, secondary 400 V 23 A.
- Other voltage meters: Agilent 34401A. S/N MY47003362. Calibration expiry date 2013-11-05.

During the CE01 and CE03 test, any emission peak, possibly identified on the analyzer data output, is thus immediately identified both on the horizontal (frequency, Hz) axis and on the vertical (current, dB μ A) axis.

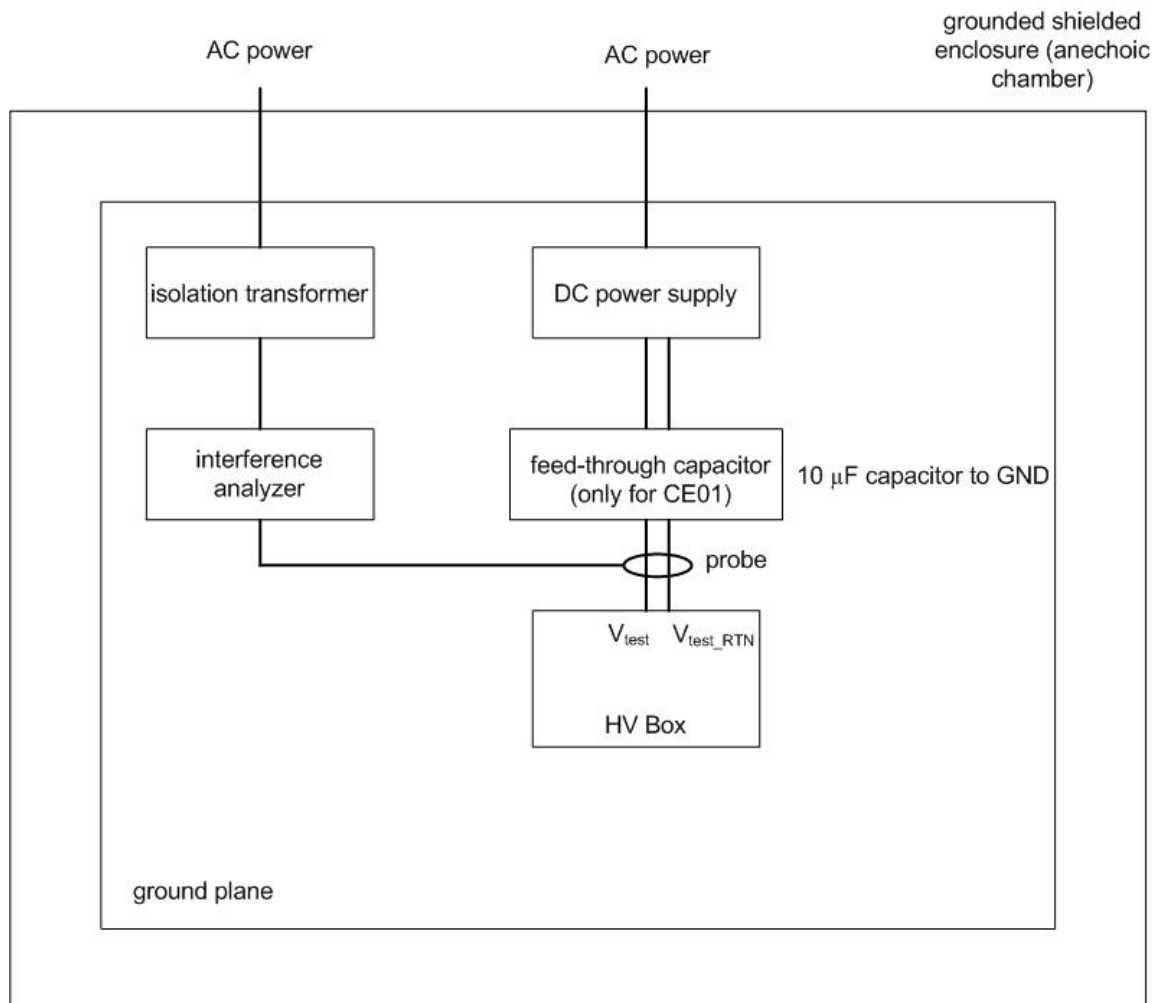


Fig. 7: test set-up configuration for CE01 and CE03 tests. V_{test} represents $V_{3.5V}$, $V_{5.6V}$, V_{28V} depending on the input line under test. V_{test_RTN} represents the corresponding return line.

4.2. CE01 test

For CE01 test the effective bandwidth of the measurement does not exceed 100 Hz. The CE01 test is passed if the limits in Tab. 2 (shown also in Fig. 8) are not exceeded for any tested power input line $V_{3.5V}$, $V_{5.6V}$, V_{28V} . Emissions greater than 20 dB below the specified limits are logged and reported in the test report, if the ambient noise is 20 dB below the specified level; otherwise, only emissions above the ambient noise are logged and reported.

Tab. 2: emission limits for CE01 test.

Frequency	CE01 emission limits (peak)
30 Hz – 200 Hz	110 dB μ A
200 Hz – 15 kHz	Decreasing log linearly with increasing frequency from 110 to 74 dB μ A

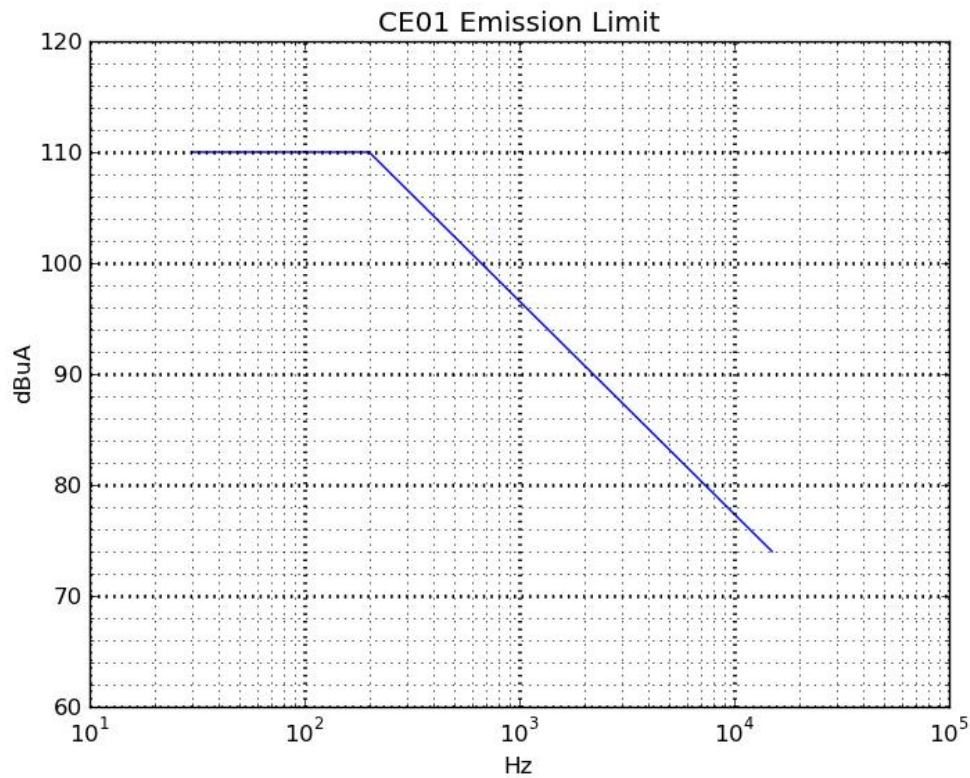


Fig. 8: emission limits for CE01 test.

4.3. CE03 test

The CE03 test is passed if the limits in Tab. 3 (shown also in Fig. 9) are not exceeded for any tested power input line $V_{3.5V}$, $V_{5.6V}$, V_{28V} . Emissions greater than 20 dB below the specified limits are logged and reported in the test report, if the ambient noise is 20 dB below the specified level; otherwise, only emissions above the ambient noise are logged and reported.

Tab. 3: emission limits for CE03 test.

Frequency	CE03 emission limits (peak)
15 kHz – 500 kHz	Decreasing log linearly with increasing frequency from 74 to 45 dB μ A
500 kHz – 50 MHz	45 dB μ A

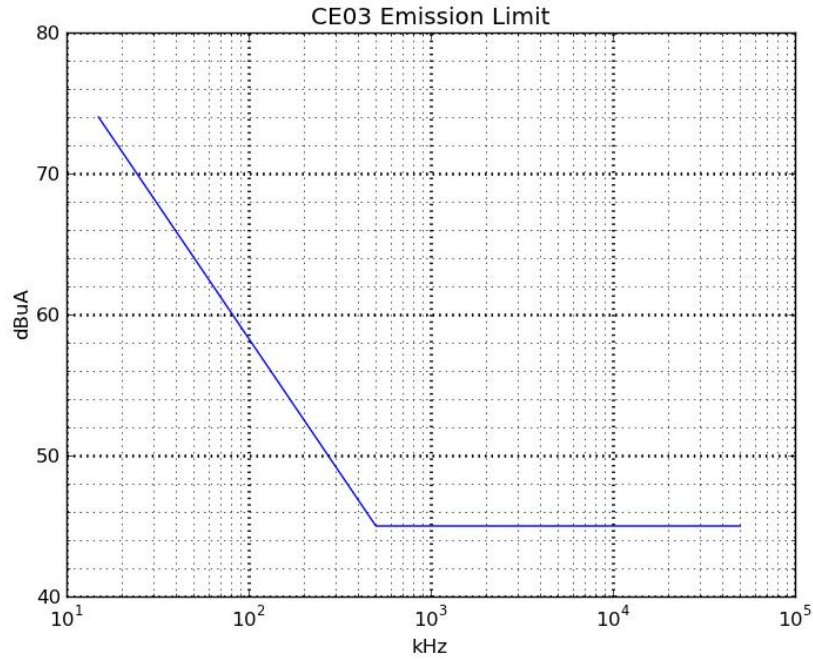


Fig. 9: emission limits for CE03 test.

4.4. Conversion factors for current probes (CE01, CE03 tests)

The conversion factors (transfer impedance, measured during the preliminary calibration for this test) between the voltage read-out on the analyzer and the current flowing in the probes are reported in Fig. 10 for probe P₂, Fig. 11 for probe P₄. The transfer impedance Z_t is expressed in dBΩ:

$$Z_t \text{ (dB}\Omega\text{)} = 20 \log_{10}(Z_t / 1 \Omega) \quad (1)$$

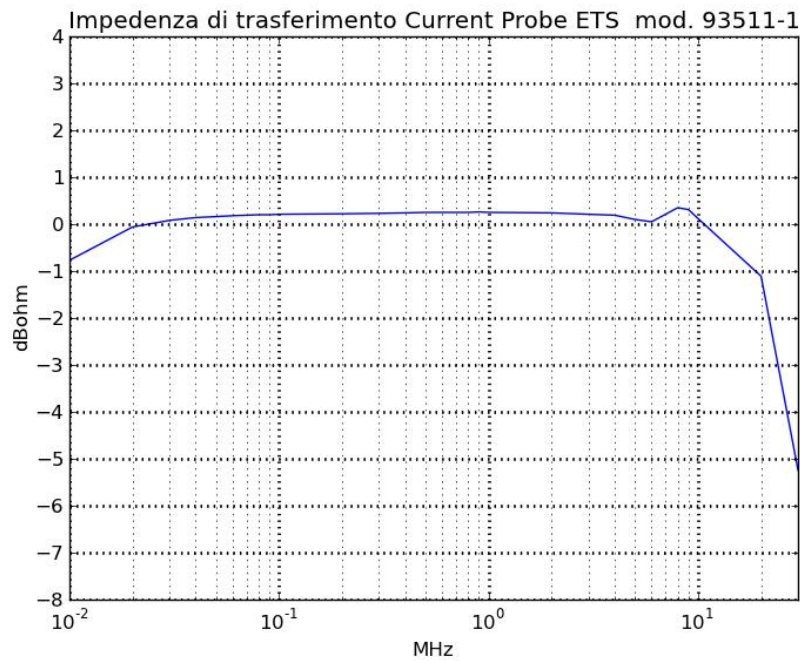


Fig. 10: transfer impedance of probe P₂

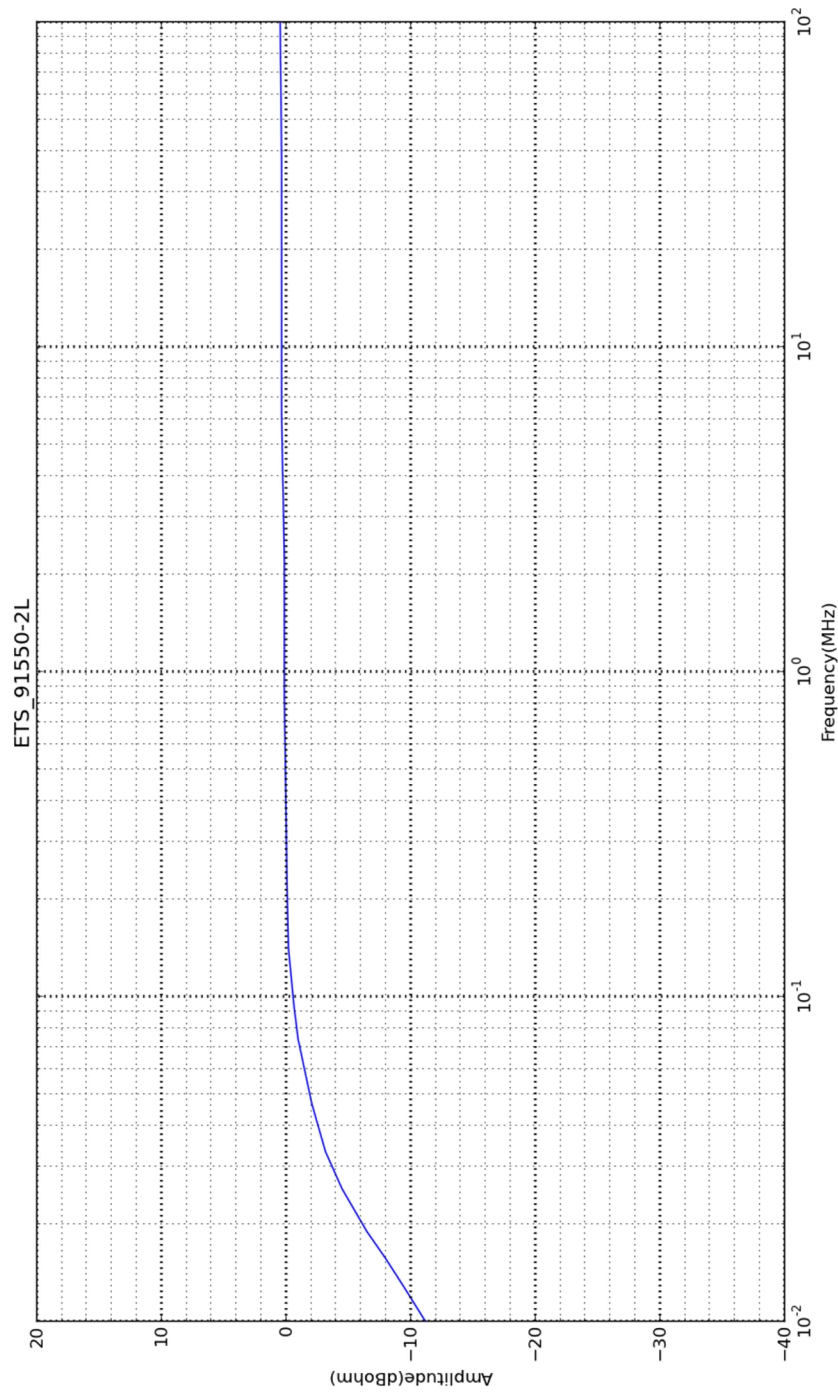


Fig. 11: transfer impedance of probe P₄.

4.5. Results (CE01, CE03 tests)

Figs. 12 and 13 show the conducted emissions measured for the power input lines of the two halves of HV Box respectively.

Specifically, Figs. 12(a)-(n) show the conducted emissions measured for input power lines +3.5V_A/P_0 <hot>, +5.6V_A/P_0 <hot>, +28V_P_0 <hot>, while Figs. 13(a)-(n) show the conducted emissions measured for input power lines +3.5V_A/P_1 <hot>, +5.6V_A/P_1 <hot>, +28V_P_1 <hot>. Applicable CE limits are also shown for comparison.

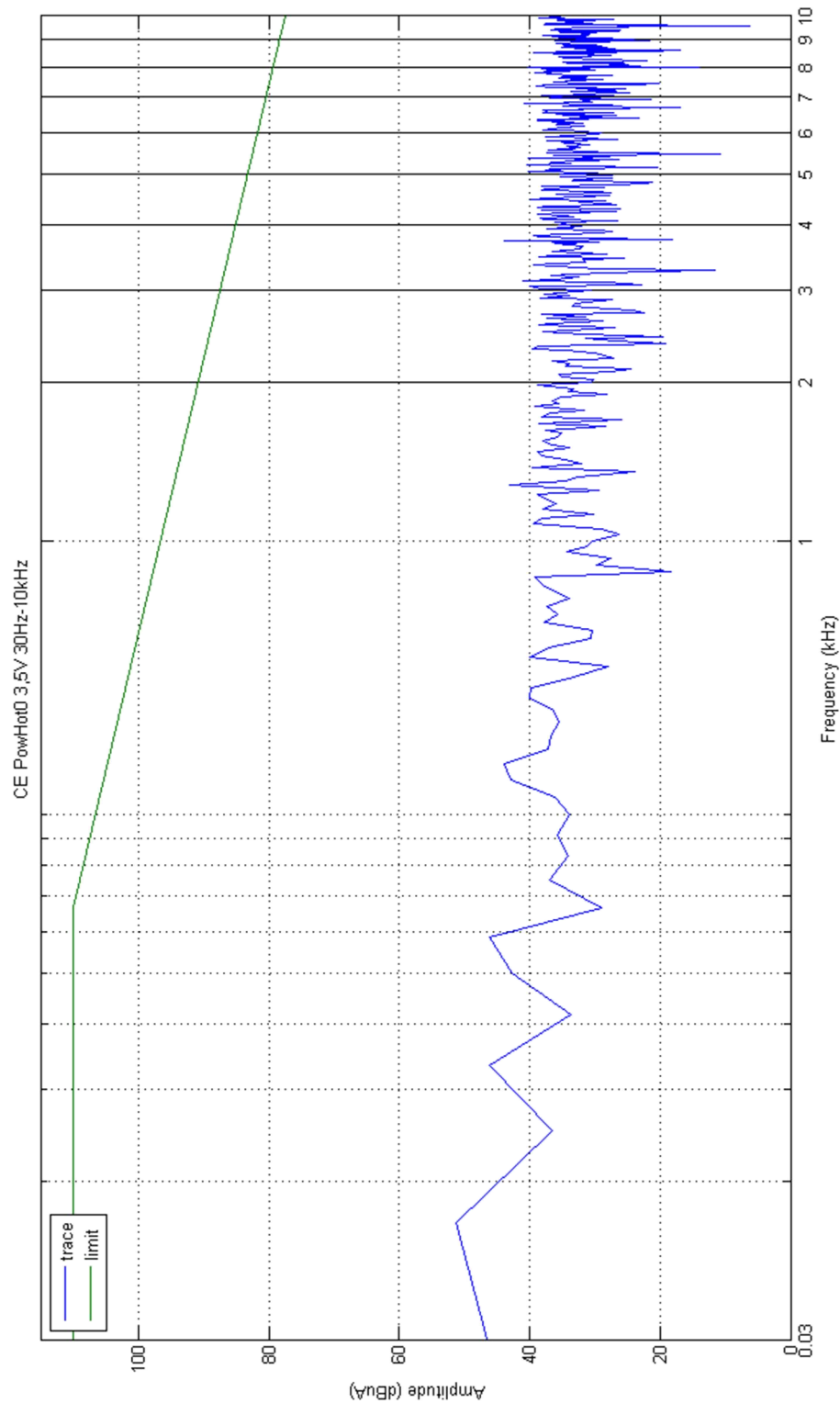


Fig. 12a

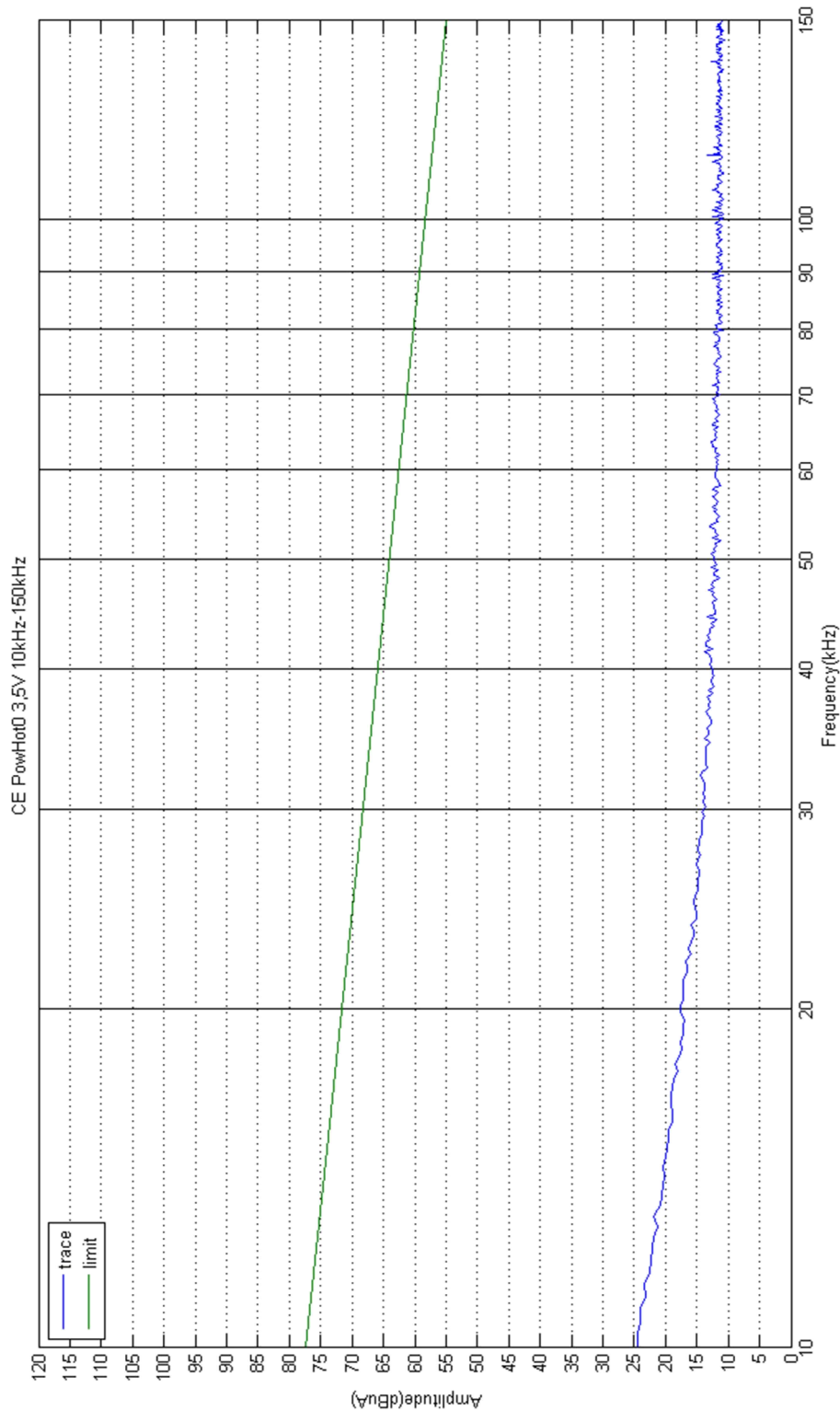


Fig. 12b

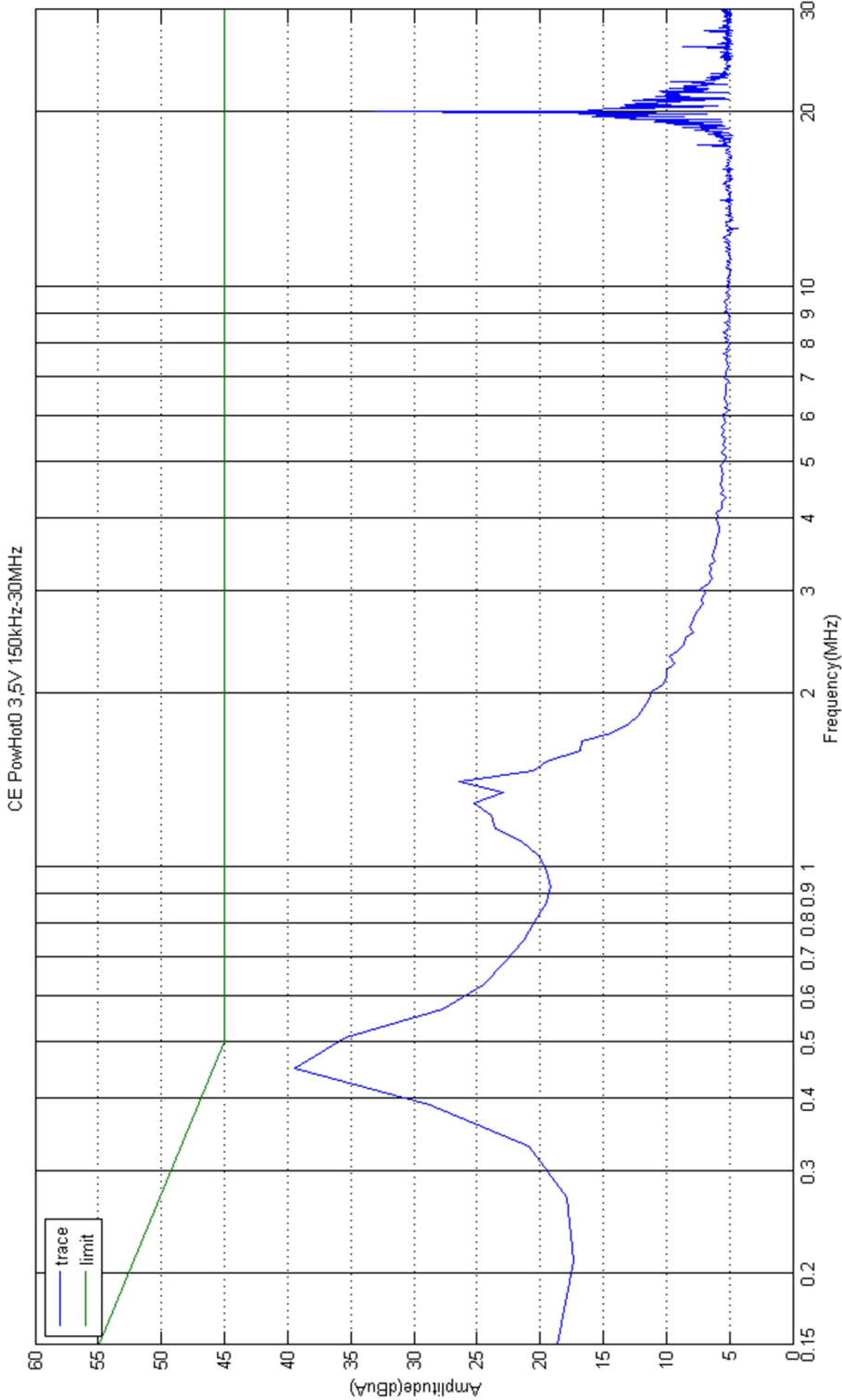


Fig. 12c

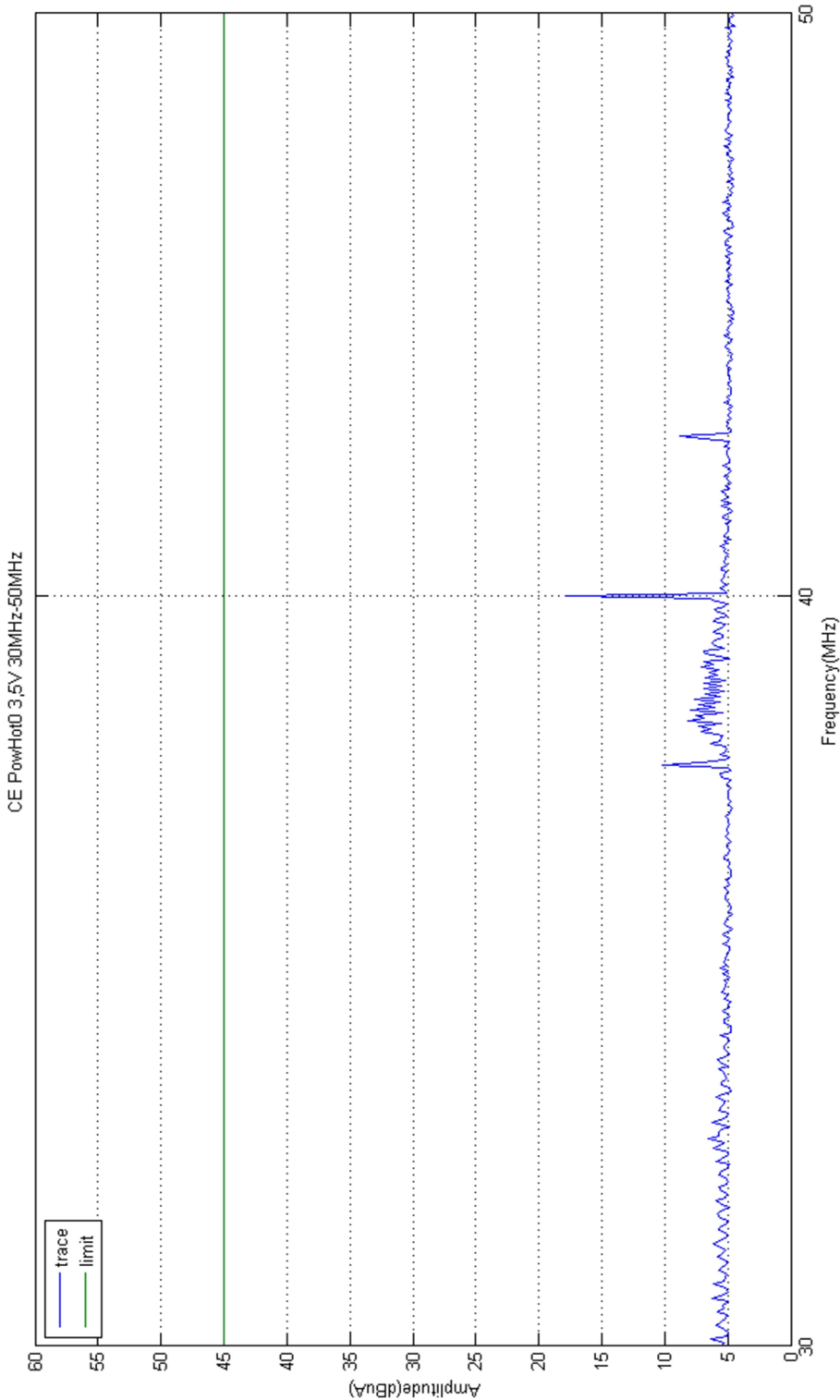


Fig. 12d

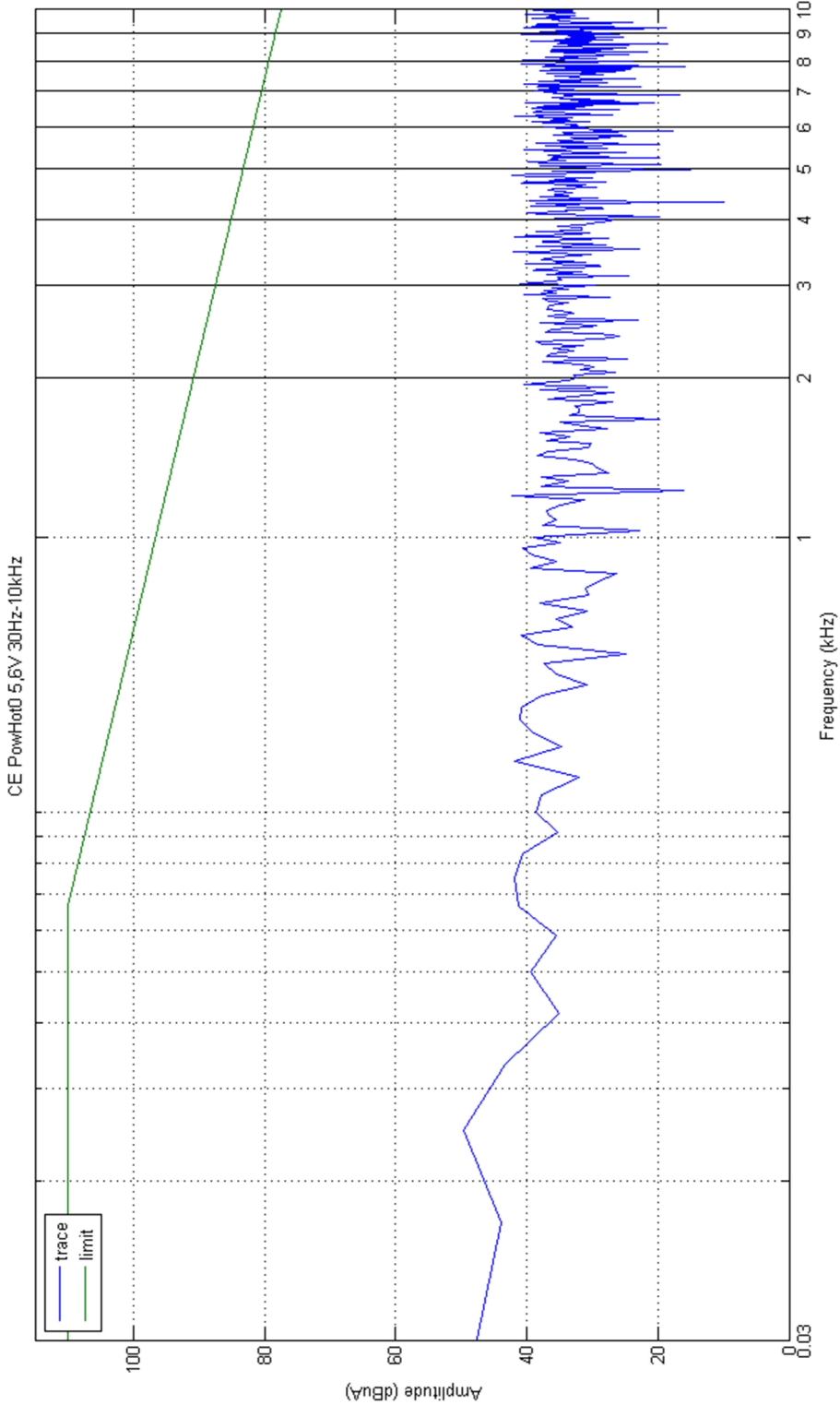


Fig. 12e

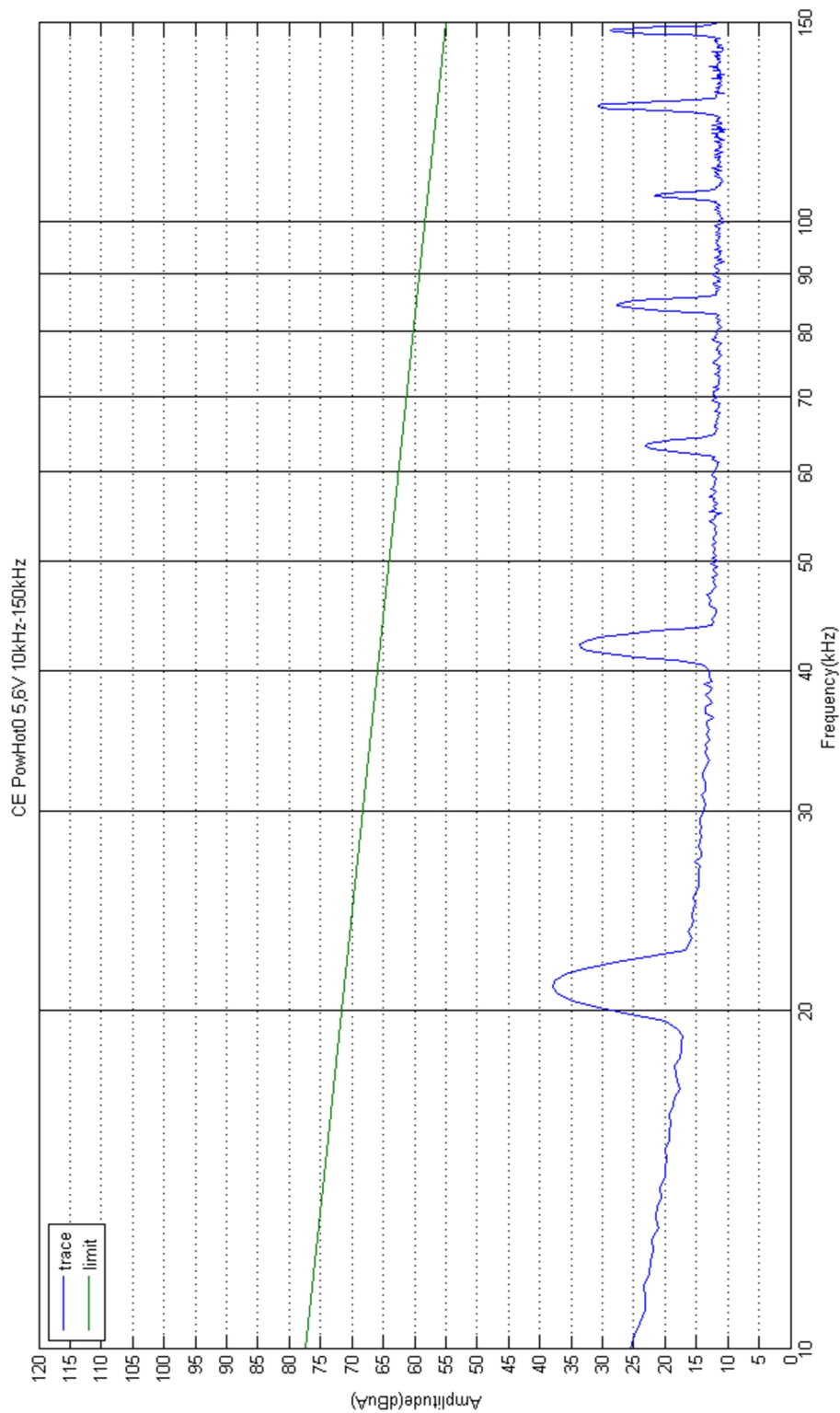


Fig. 12f

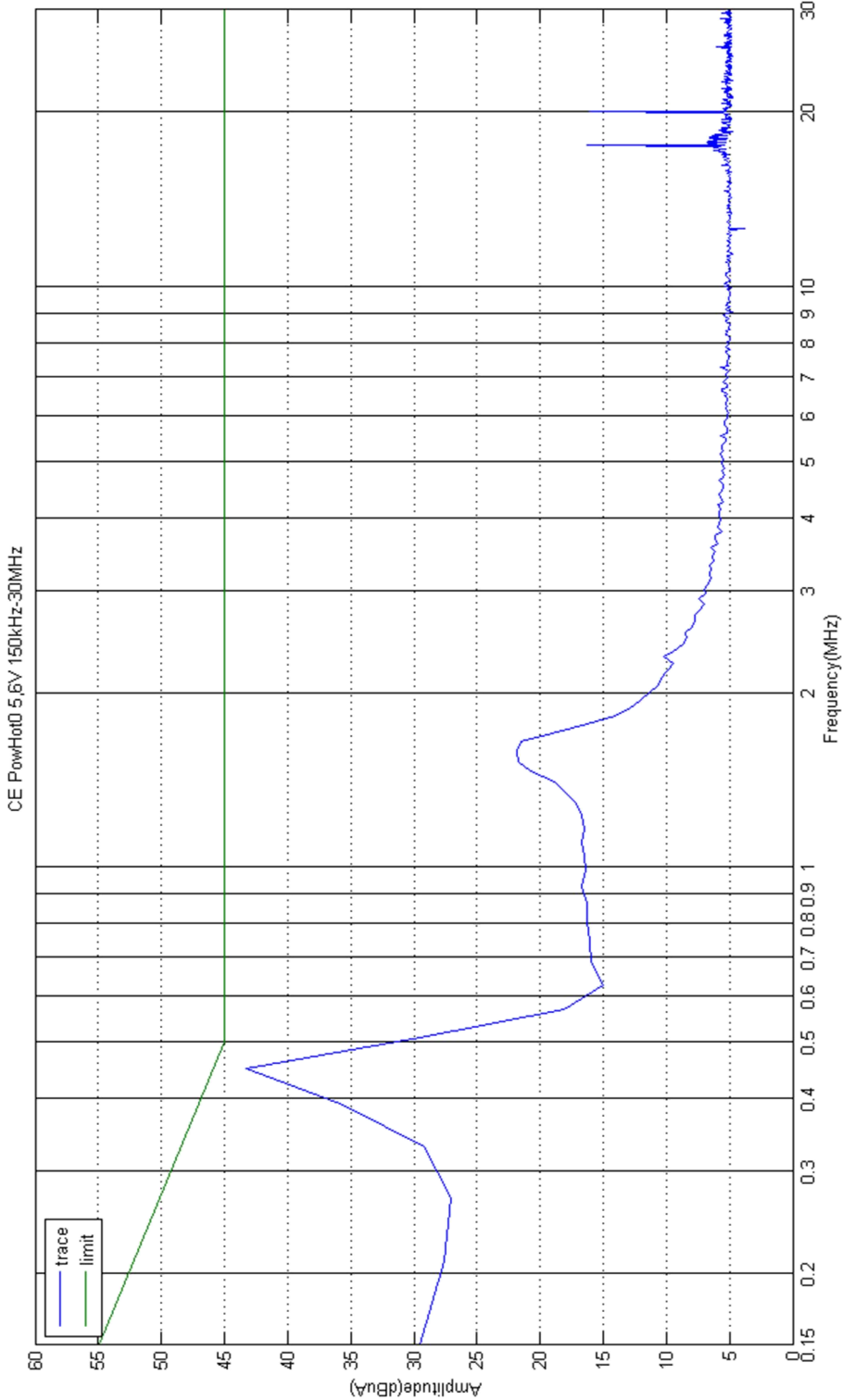


Fig. 12g

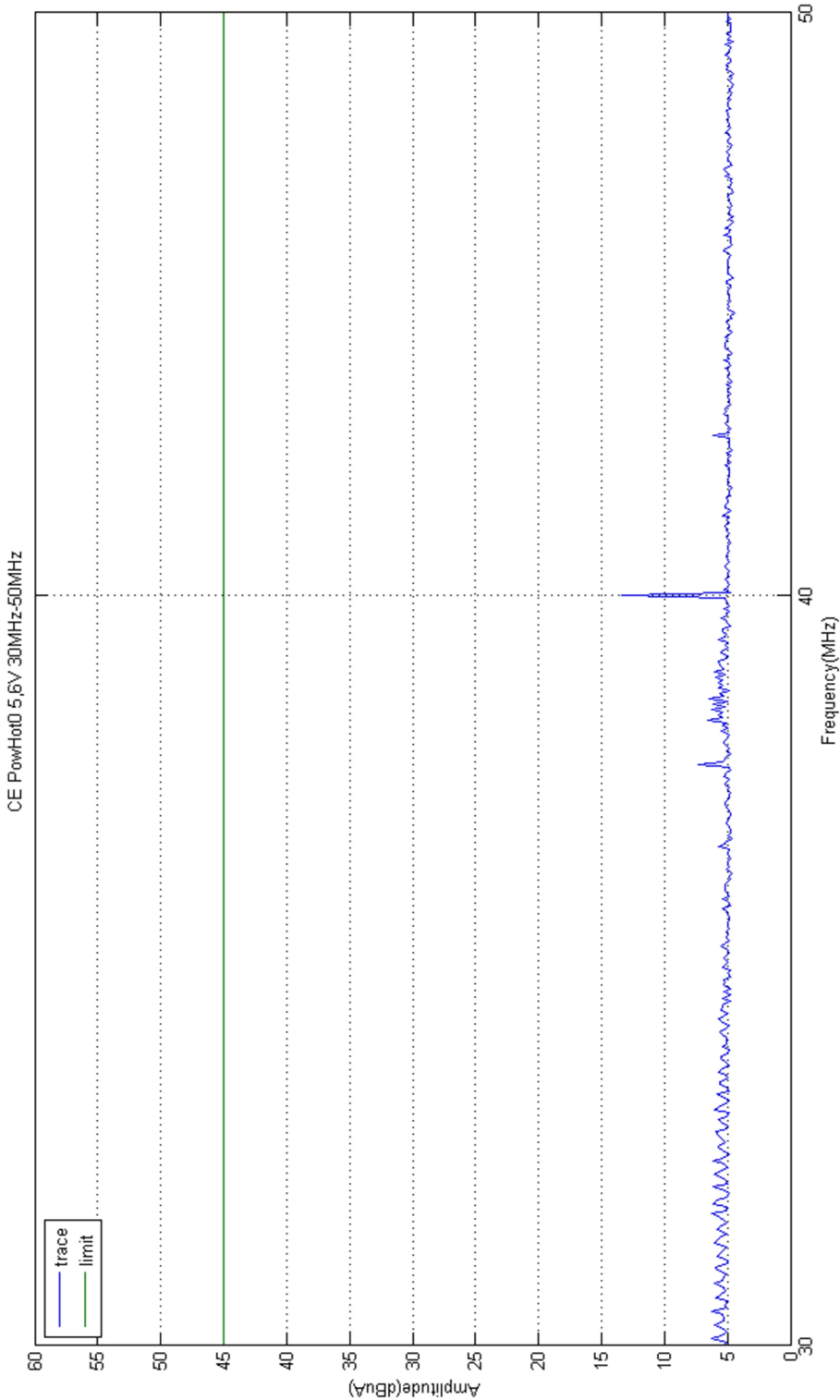


Fig. 12h

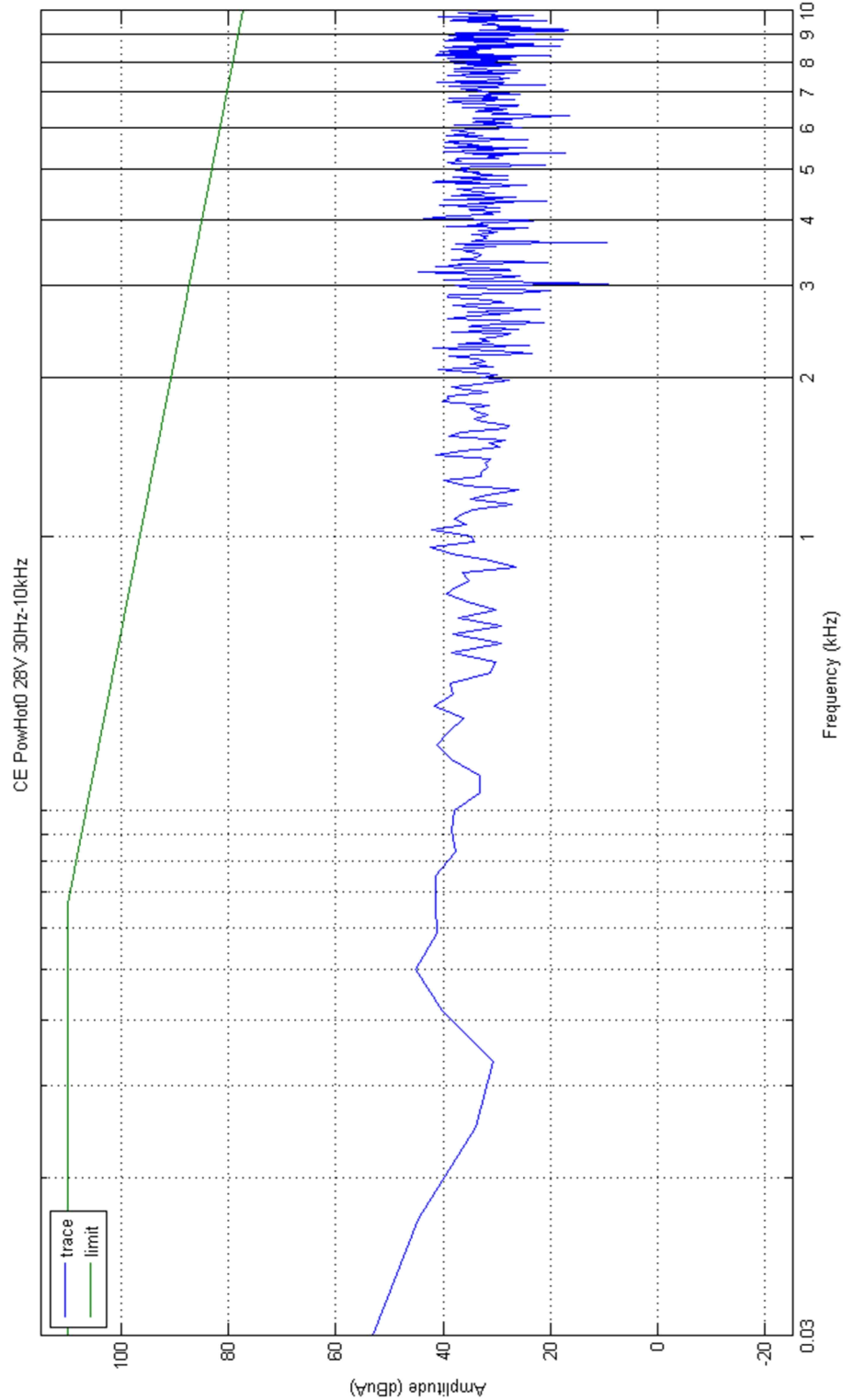


Fig. 12i

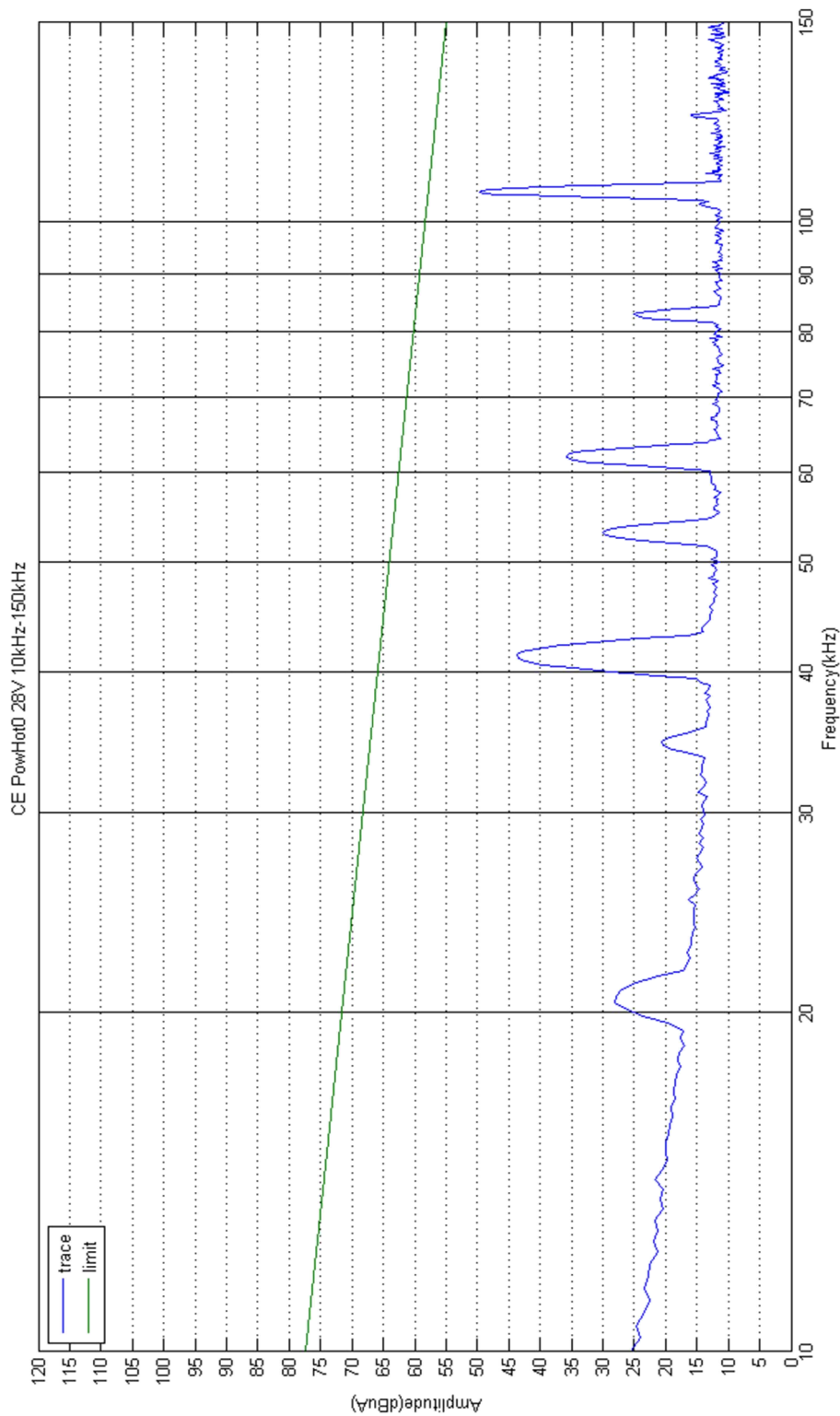


Fig. 12/

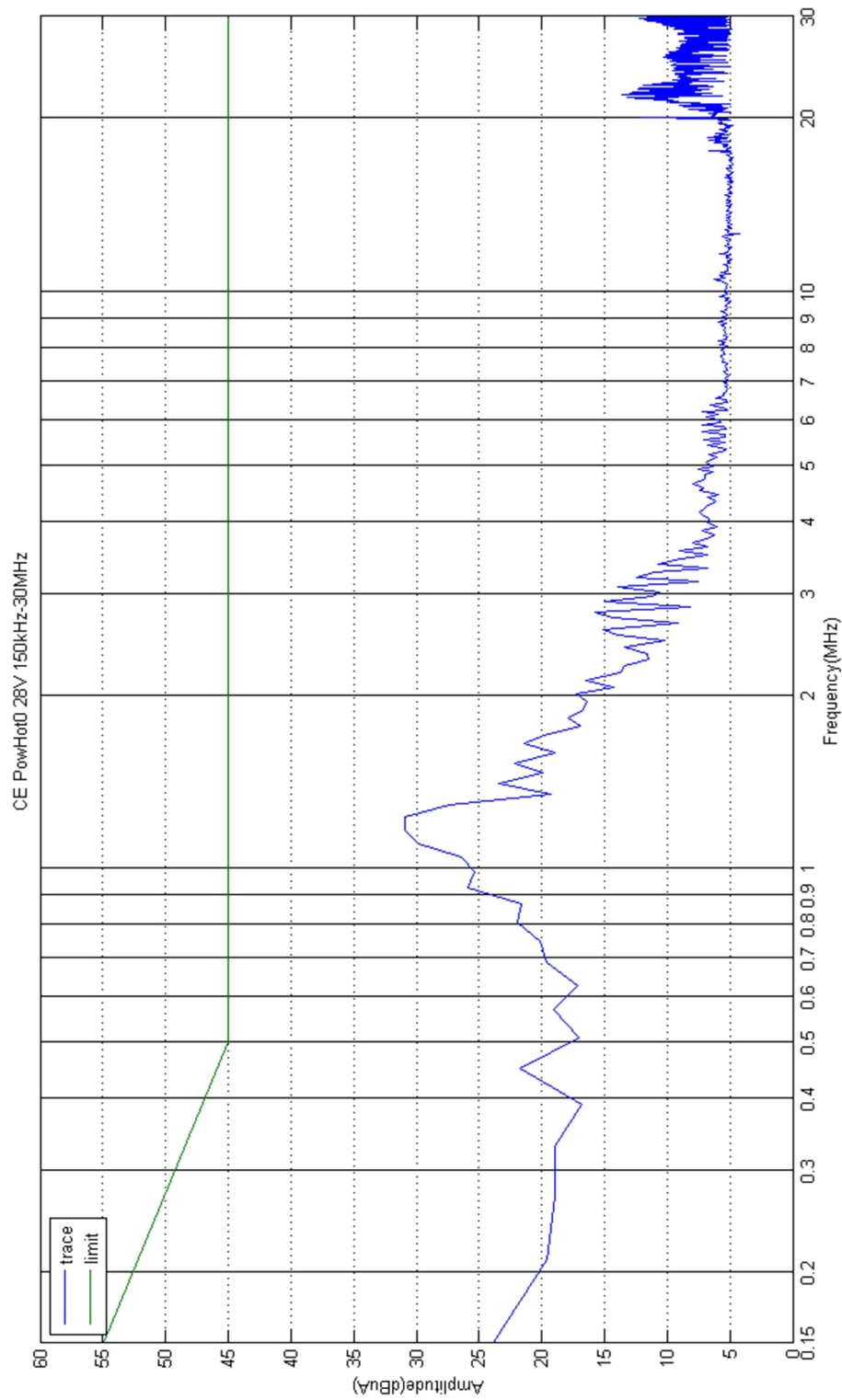


Fig. 12m

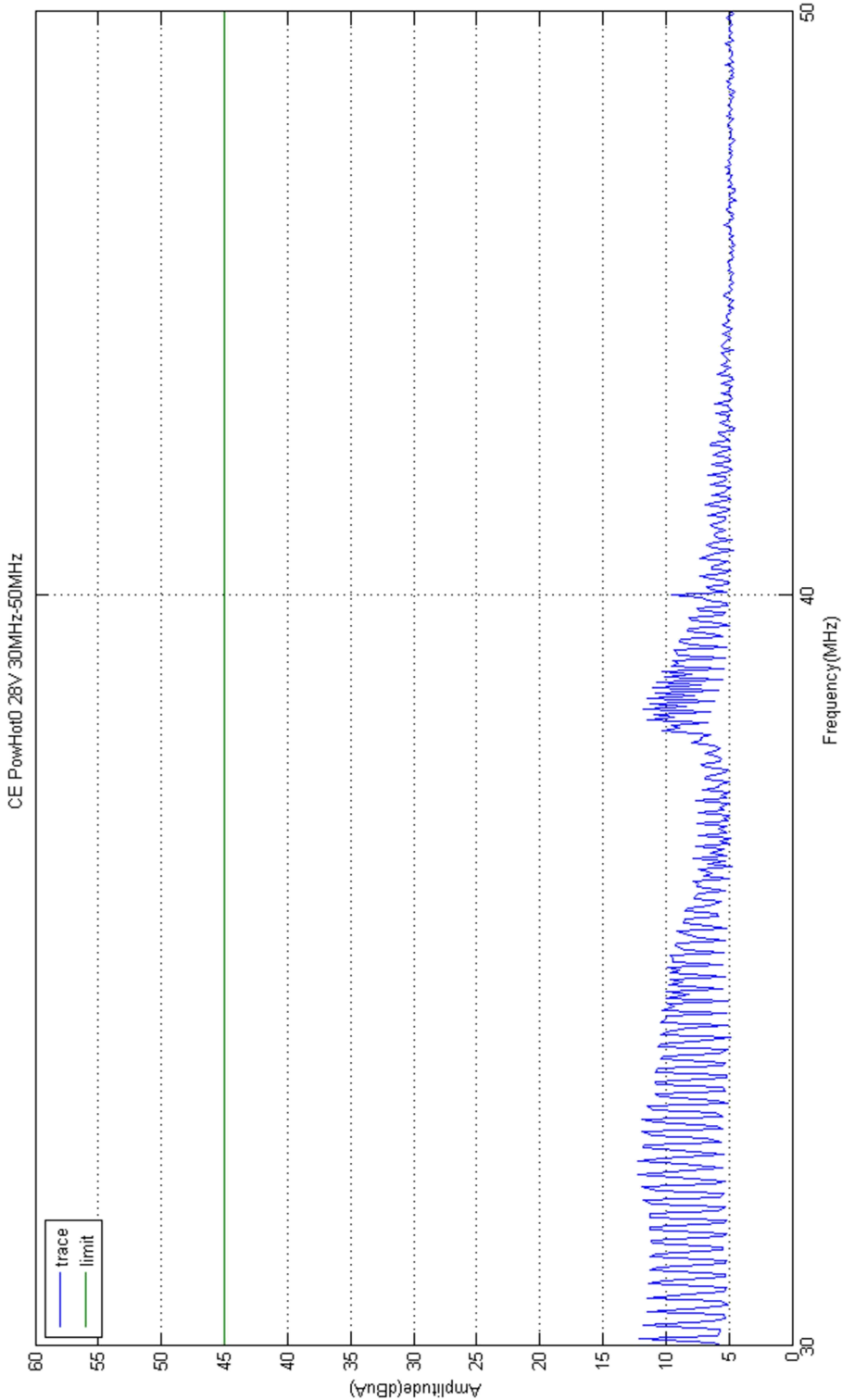


Fig. 12n

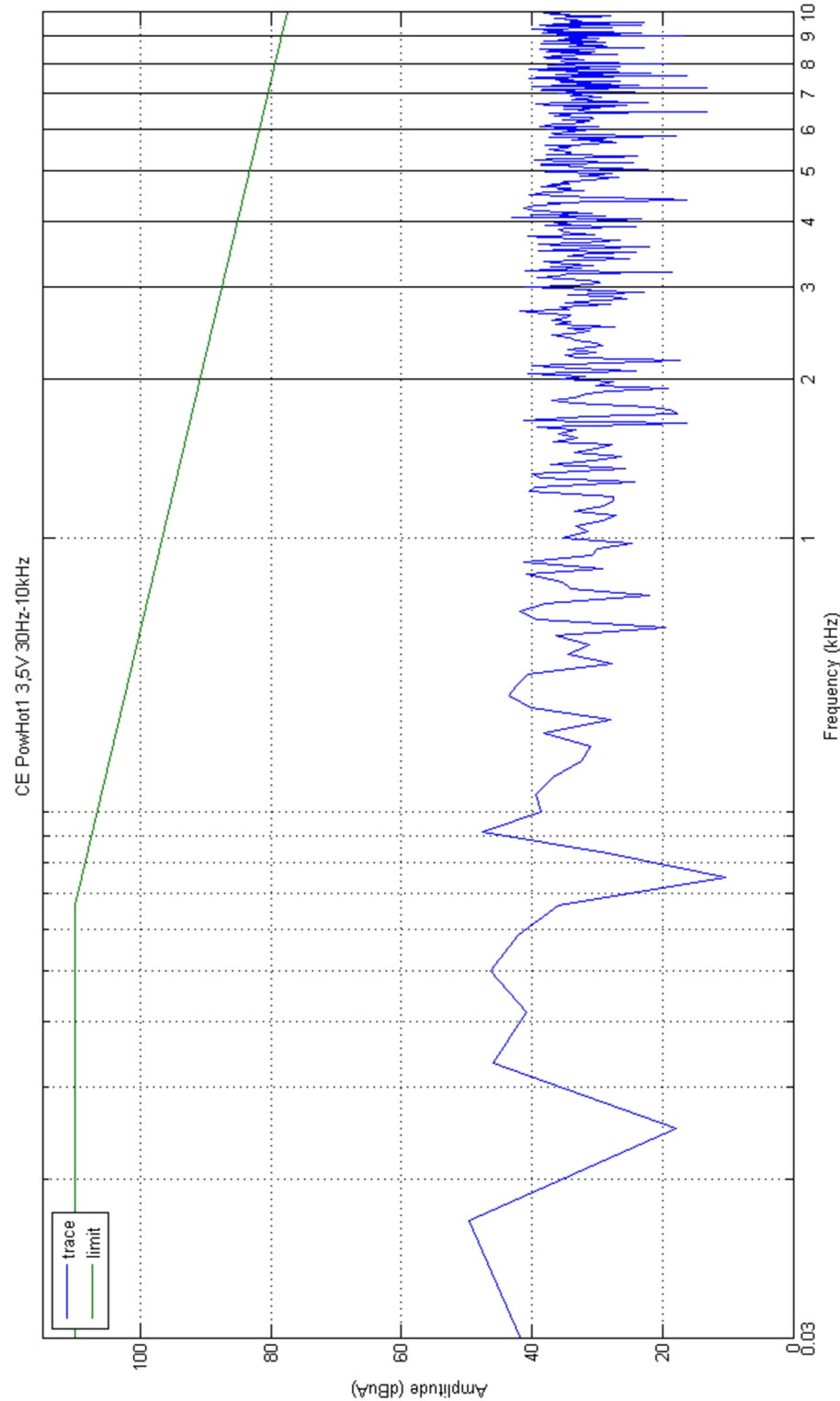


Fig. 13a

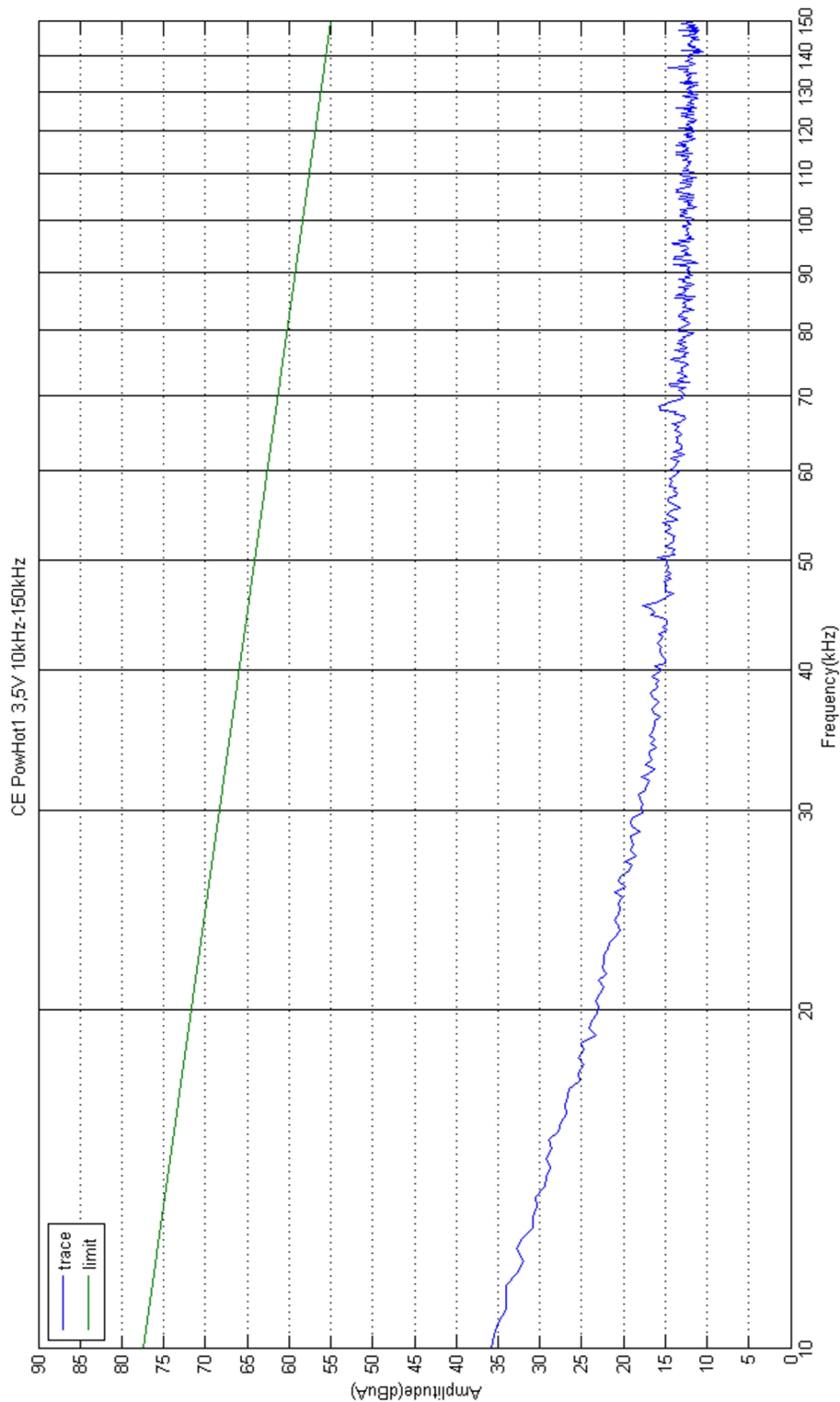


Fig. 13b

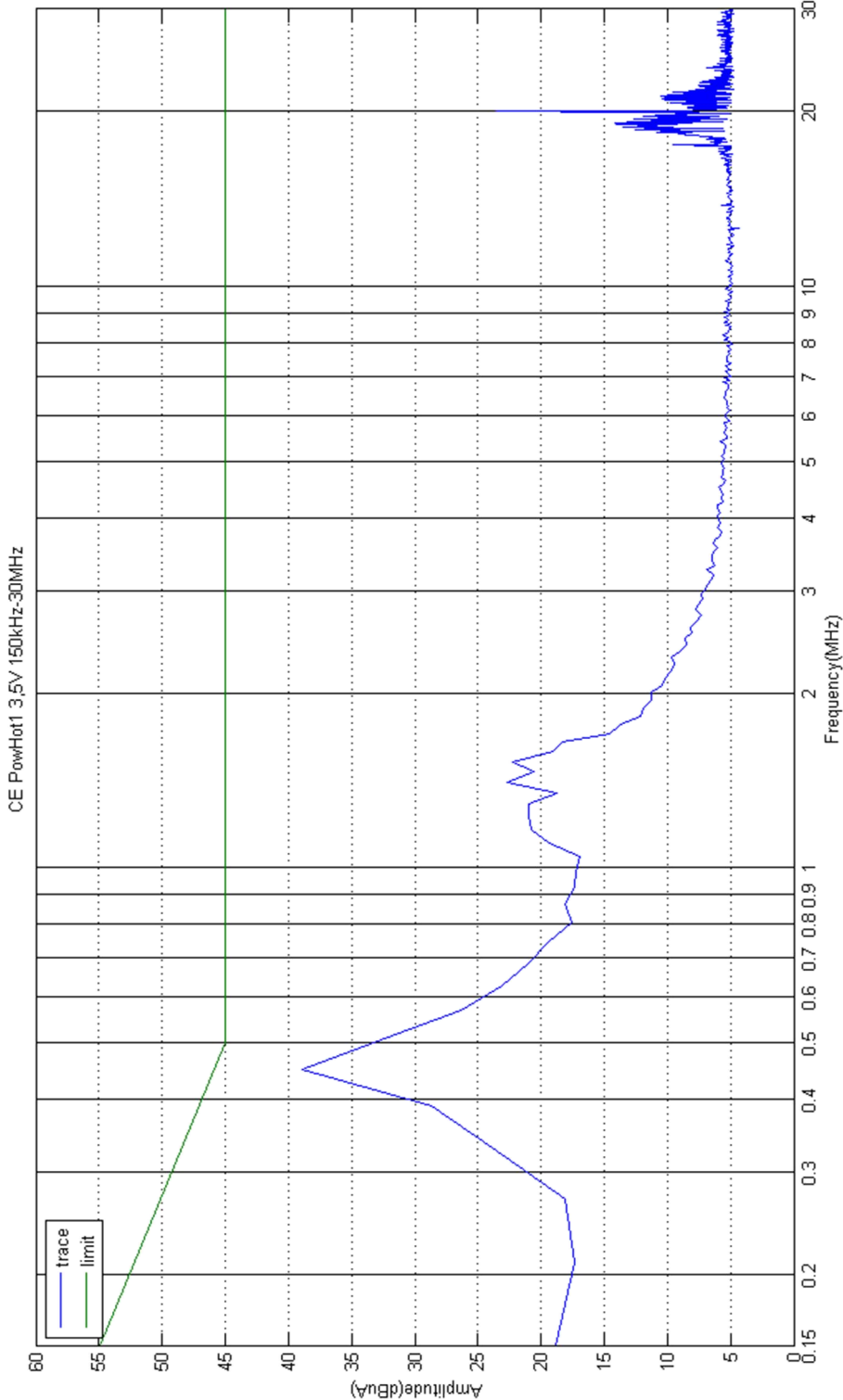


Fig. 13c

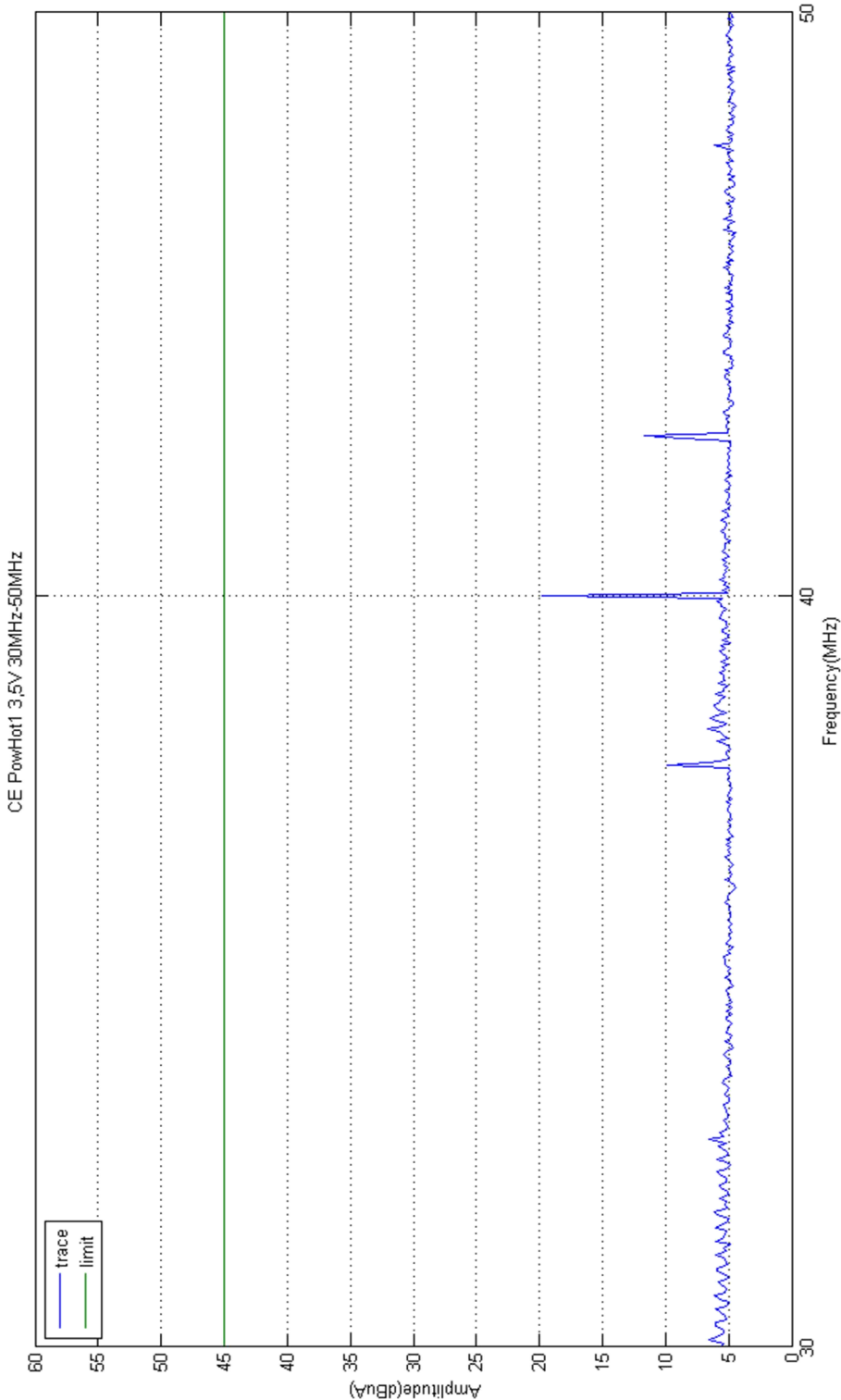


Fig. 13d

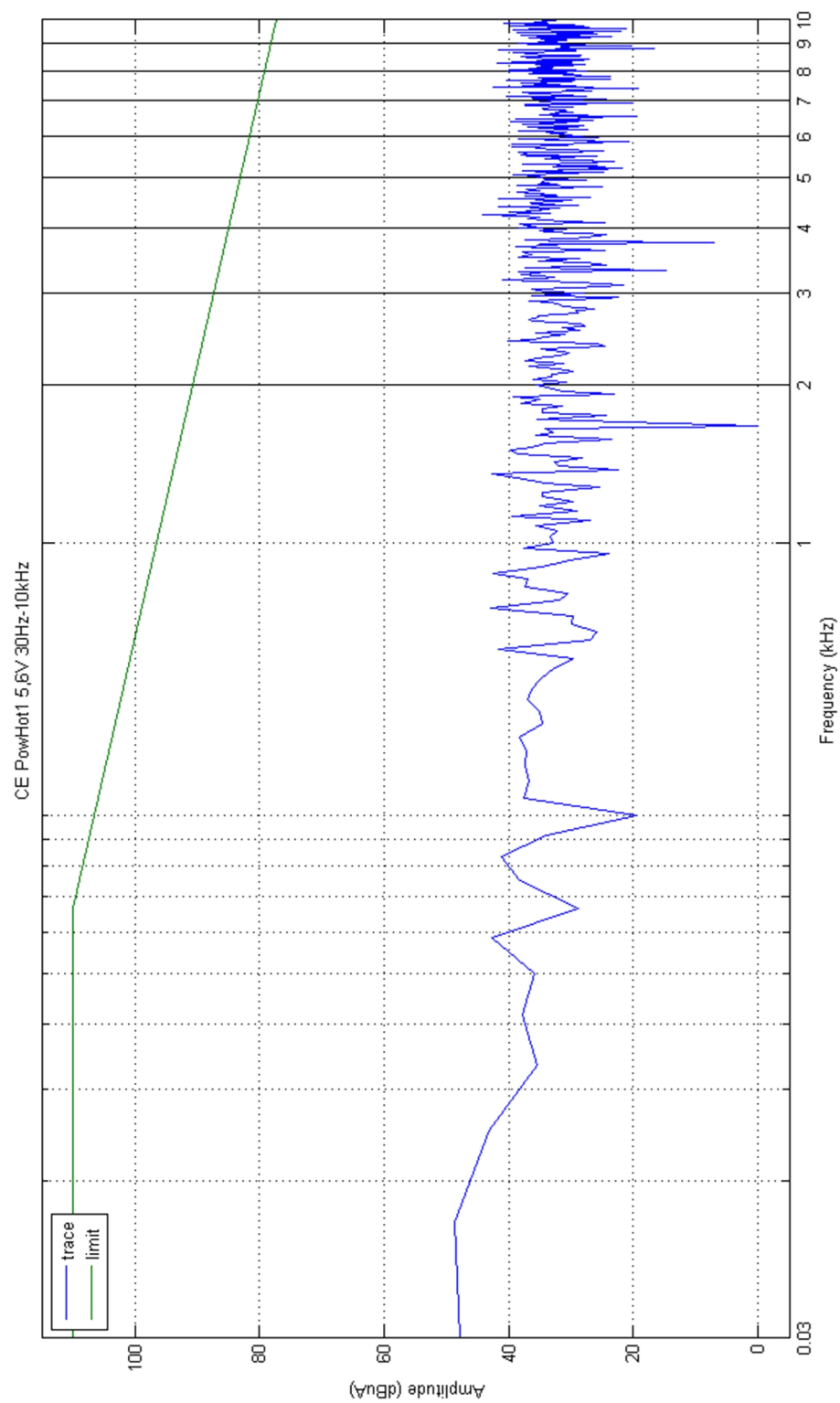


Fig. 13e

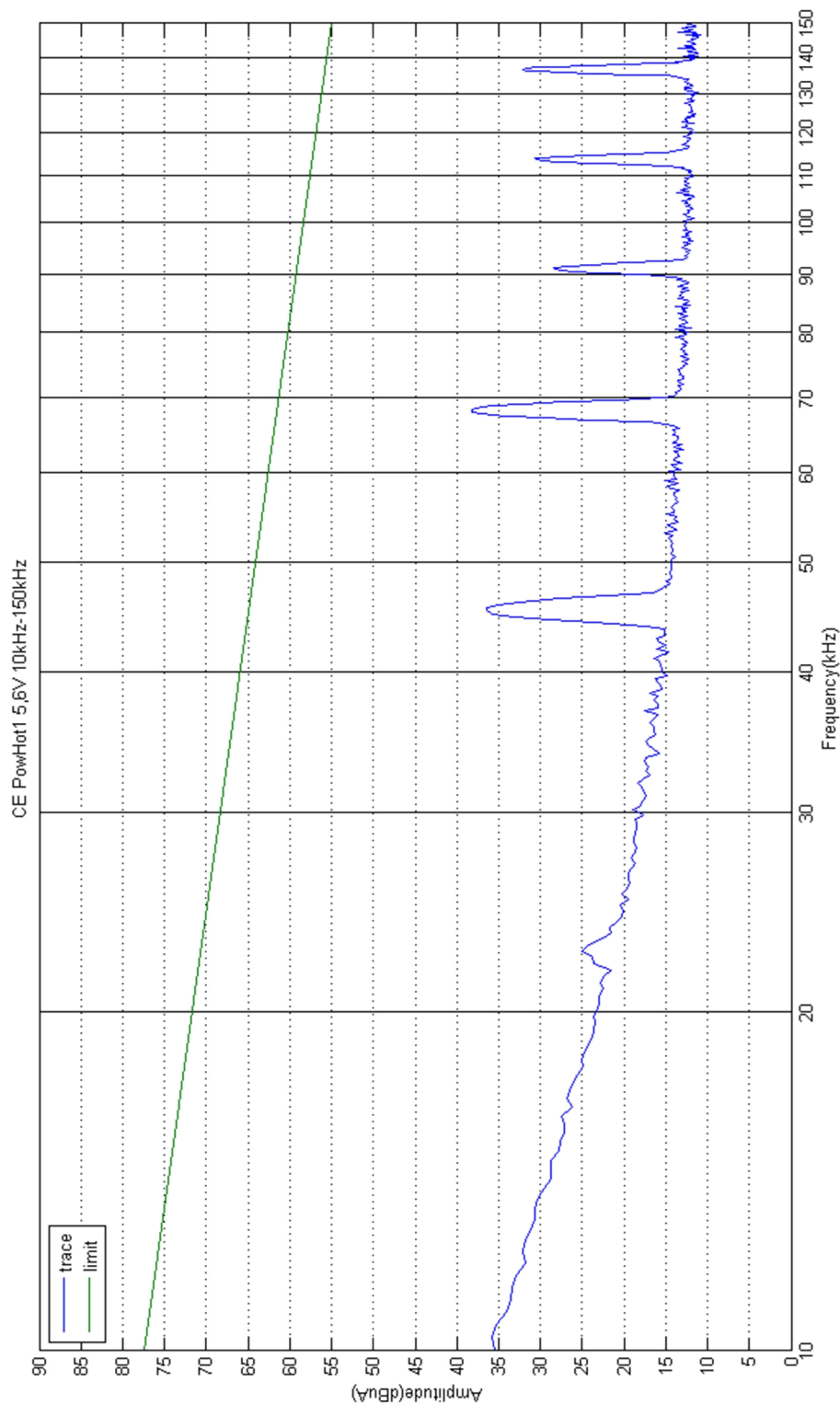


Fig. 13f

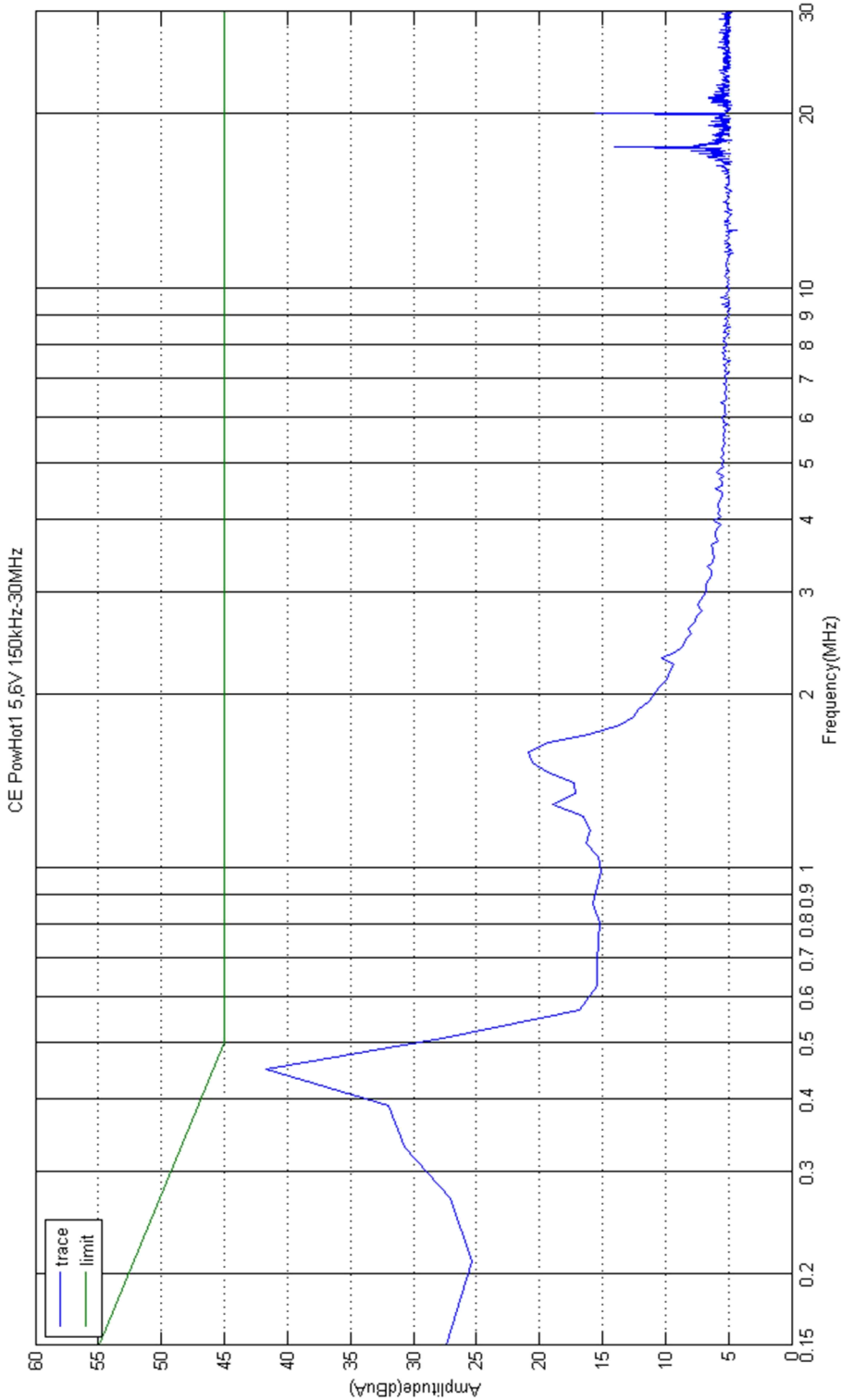


Fig. 13g

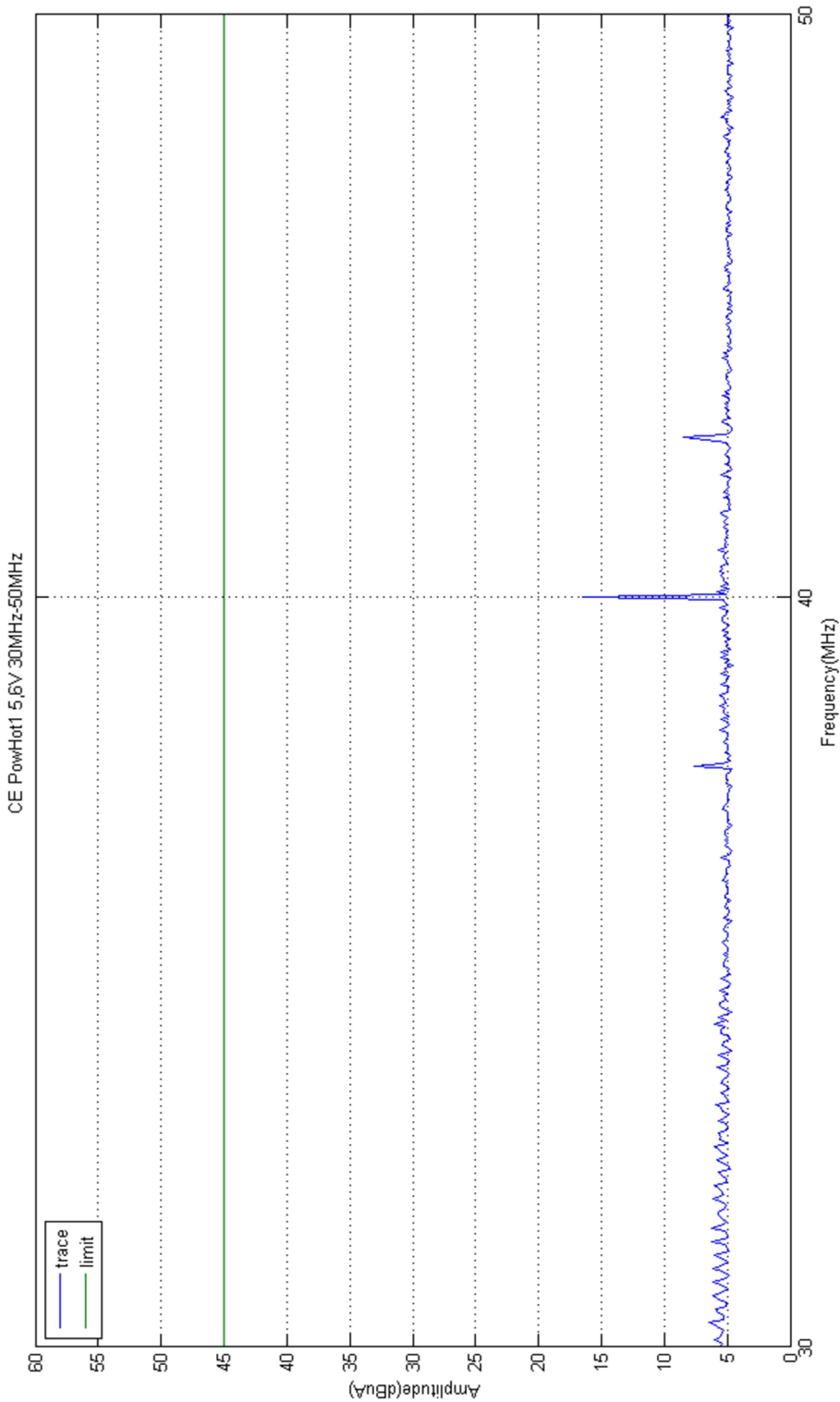


Fig. 13*h*

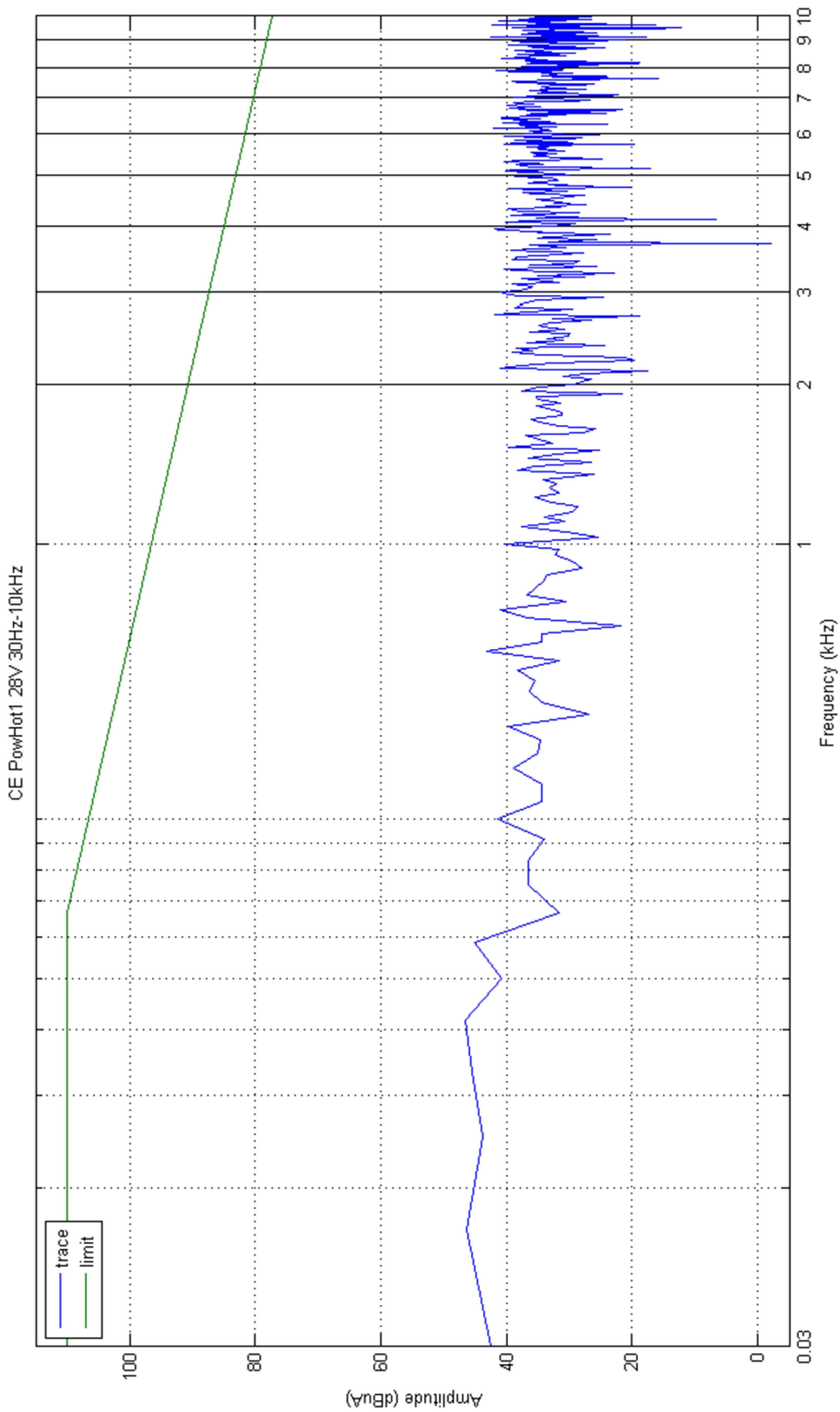


Fig. 13i

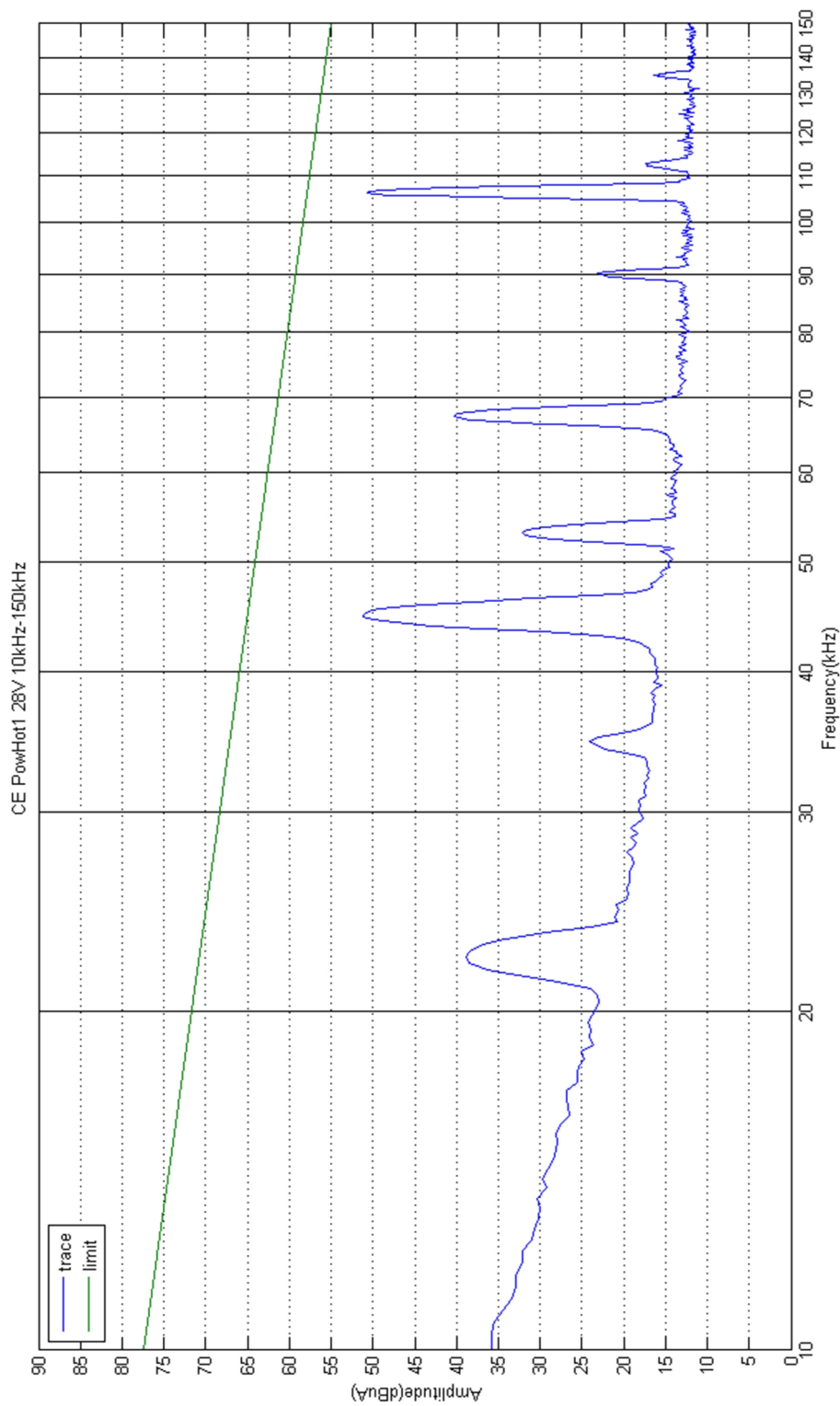


Fig. 13/

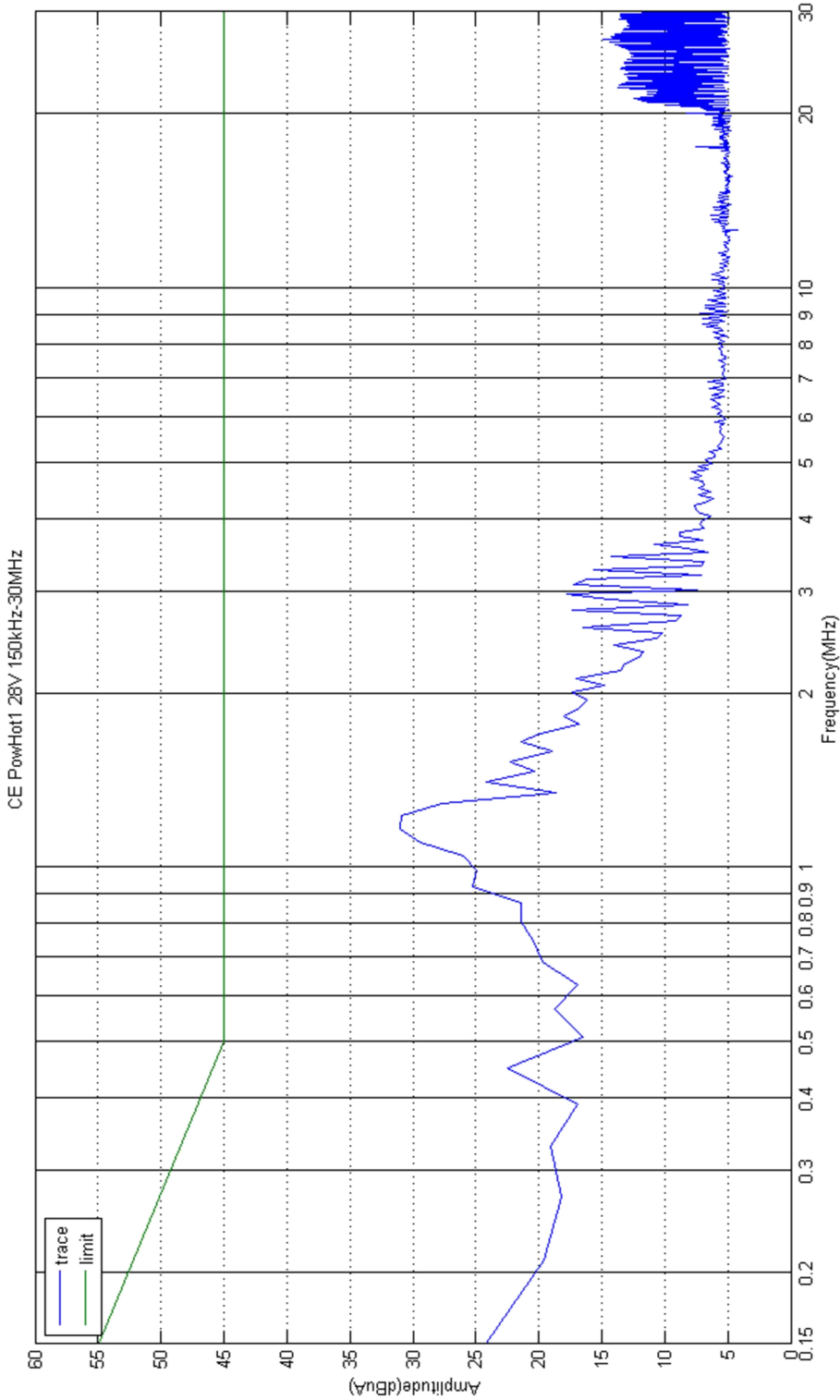


Fig. 13m

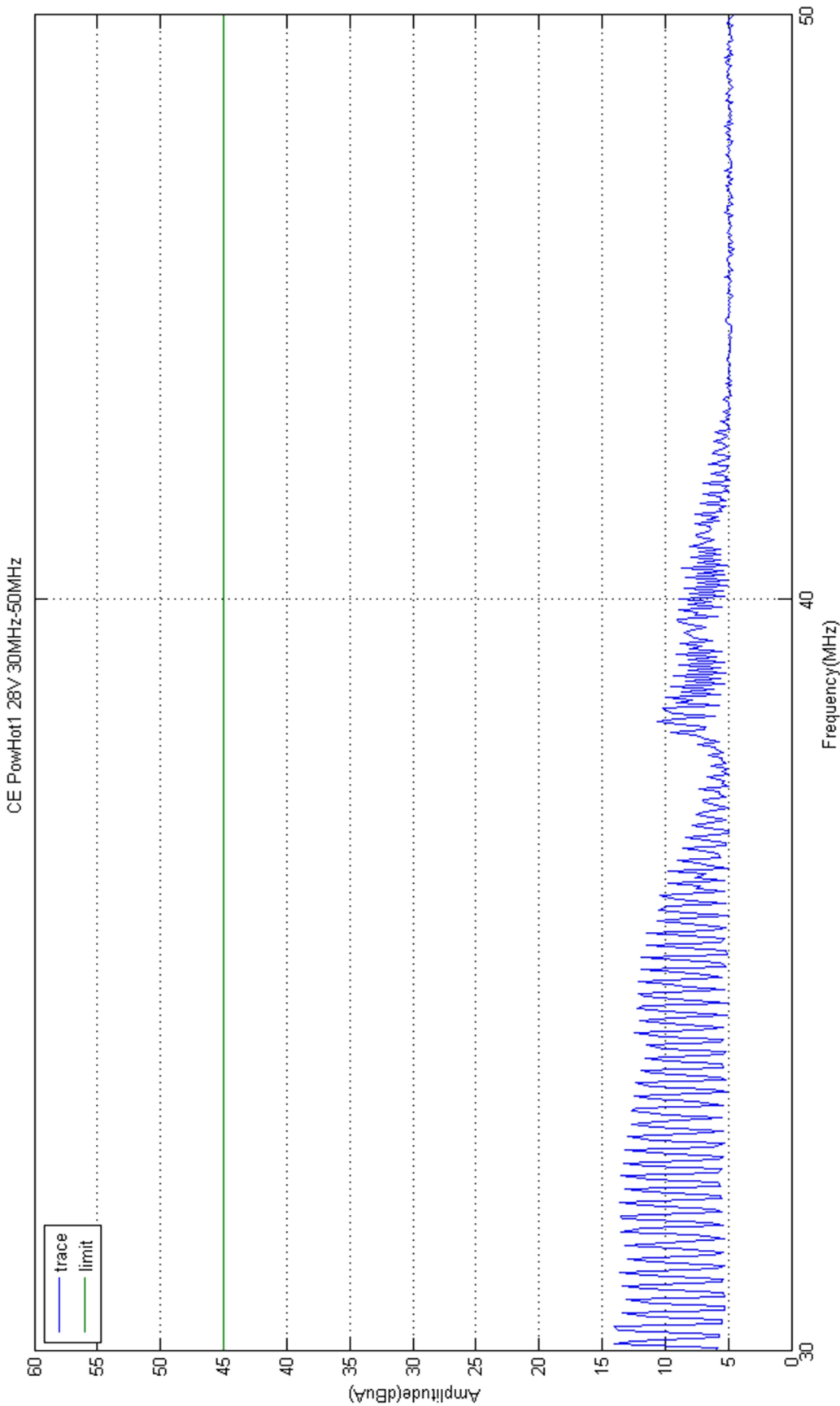


Fig. 13n

5. CE07 test

5.1. Configuration (CE07 test)

The configuration implemented for this test is shown in Fig. 14. The circuit breaker shown is characterized by negligible transient effects (mercury switch).

Each input power line of the HV Box is separately tested. The transient voltages V_1 and V_2 are measured, by using two oscilloscope probes; the resulting voltage difference $V_1 - V_2$ is recorded. The CE07 test is passed if the limits in Tab. 4 (shown also in Fig. 15) are not exceeded for any tested power input line: $V_{3.5V}$, $V_{5.6V}$, V_{28V} .

Employed equipment is listed below.

- Voltage meter V_1 , V_2 : oscilloscope Lecroy Waverunner 6100A.
- Power supplies, current meters:
 - Agilent U8032A. S/N MY52180017. Calibration expiry date 2013-05-03.
 - TTI QL355T. S.N. 346658. Current meter cross-calibrated with Agilent U8032A.
- Other voltage meters: Agilent 34401A. S/N MY47003362. Calibration expiry date 2013-11-05.
- LISN: EMCO 3825/2.
- Mercury switch: ASSEMtech S1017.
-

Tab. 4: emission limits for CE07 test.

Time after power-up (μ s)	CE07 emission limits for each line (V)		
	+3.5V	+5.6V	+28V
0.1 – 10	5.25	8.4	42.0
10 – 50	Decreasing log linearly with increasing time from the above value to:		
	4.2	6.72	33.6
50 – 10^3	9.5	11.6	34.0
10^3 – 10^4	4.0	6.1	29.68
10^4 – 10^5	4.0	6.1	29.4

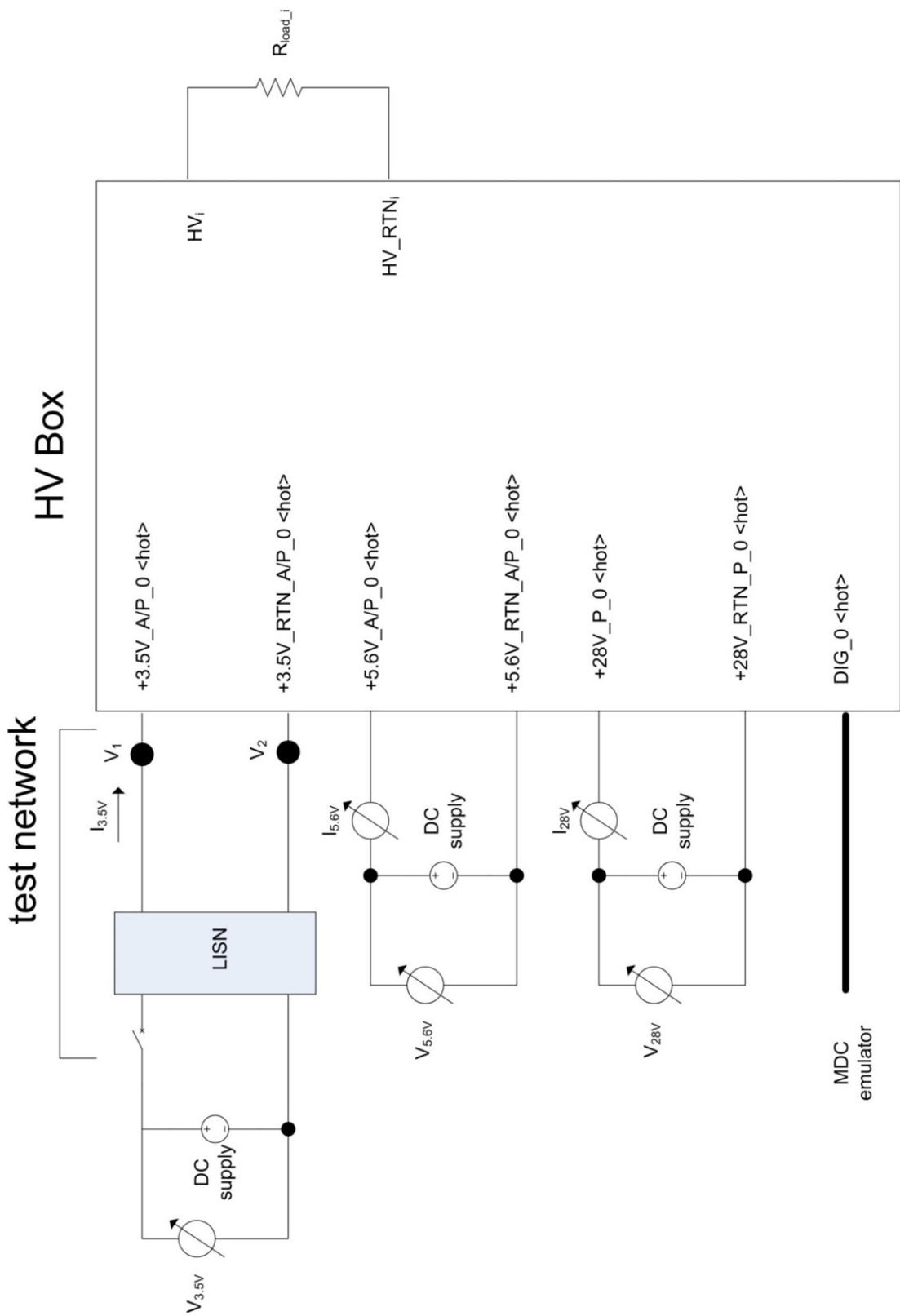
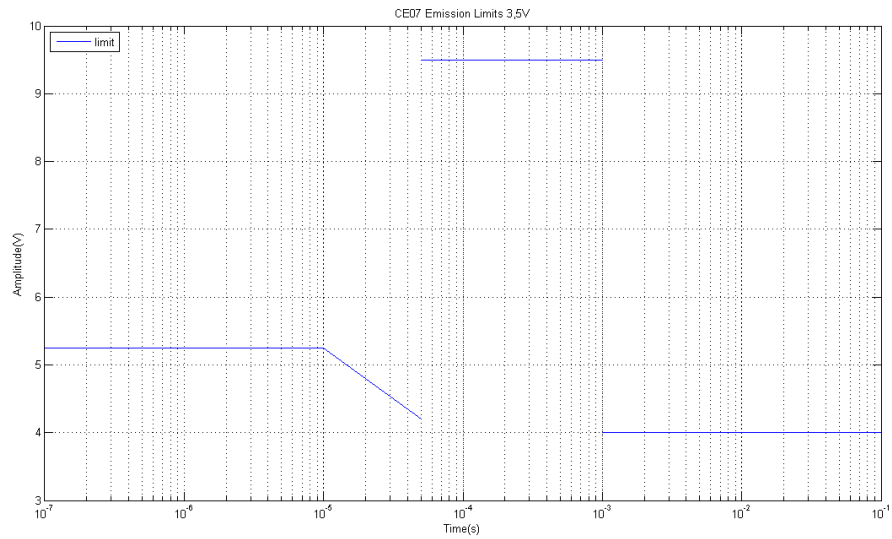
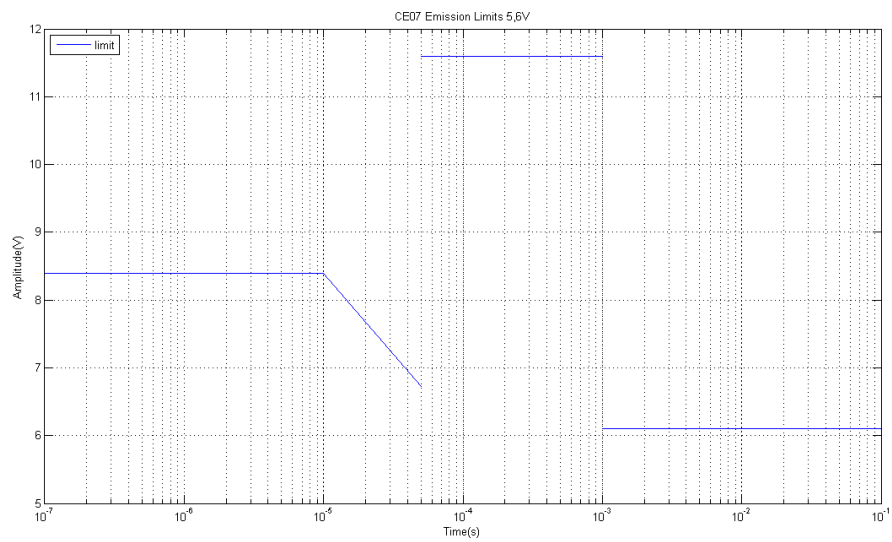


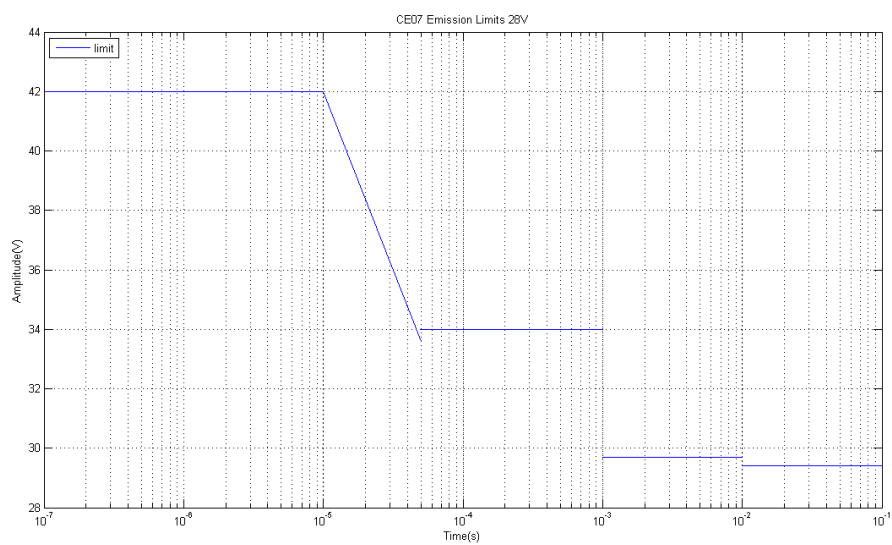
Fig. 14: test circuit configuration for CE07 test of $+3.5V_A/P_0 <hot>$ line. For test of corresponding “_1” line, the configuration is obtained by substituting “_0” with “_1” in figure. Configurations for CE07 test of other power lines ($+5.6V_A/P_0 <hot>$, $+28V_P_0 <hot>$) are similar to this one: the test network is applied only to the power line under test.



(a)



(b)



(c)

Fig. 15 (a)-(c): emission limits for CE07 test.

5.2. Results (CE07 test)

The measurement of each single waveform has been repeated at least 5 times, with data showing consistency of the various measurements within 20%. To characterize the implemented set-up, a dedicated measurement has been performed with a resistive load (12 Ω) instead of the HV Box power input, and +5 V set on the power supply; the result is shown in Fig. 16. A selection of the CE07 test measurements is reported in Figs. 17-28.

During the test, a non-conformity has been found, concerning the measured input waveform during CE07 test; a corresponding request for waiver has been issued and accepted by ASI and JAXA.

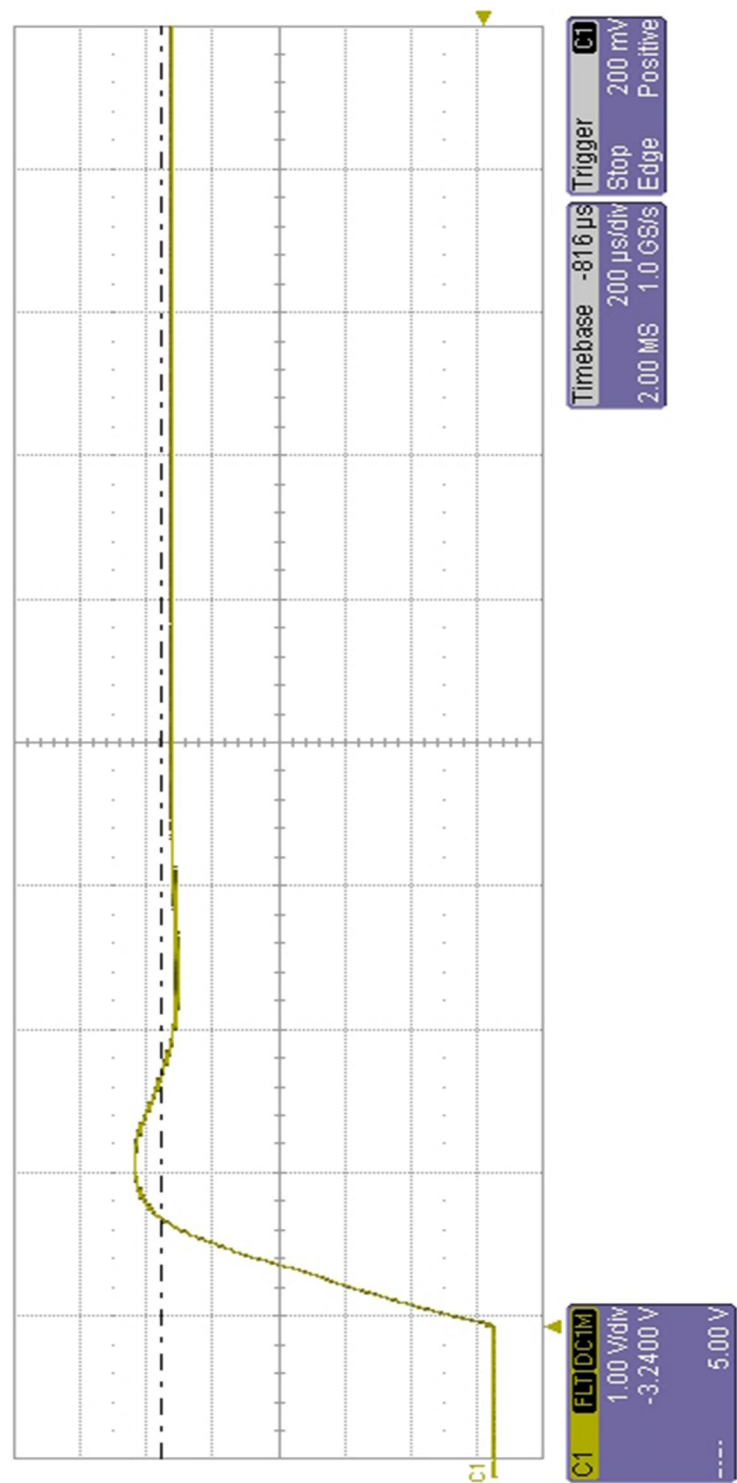


Fig. 16: power-on waveform obtained with a resistive load instead of the HV Box power input.

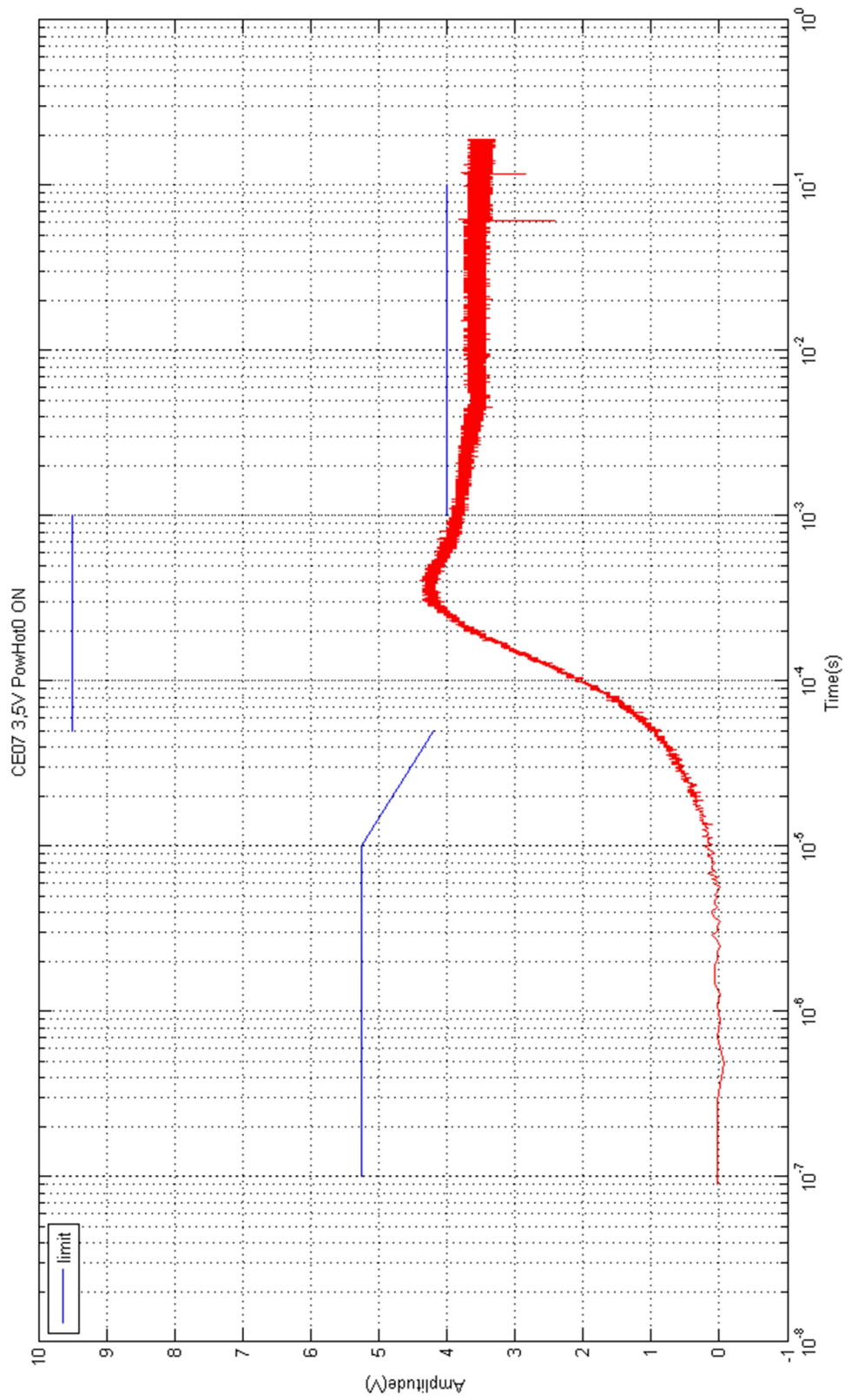


Fig. 17: power-on waveform for V_1 - V_2 on +3.5V_A/P_0 <hot> line.

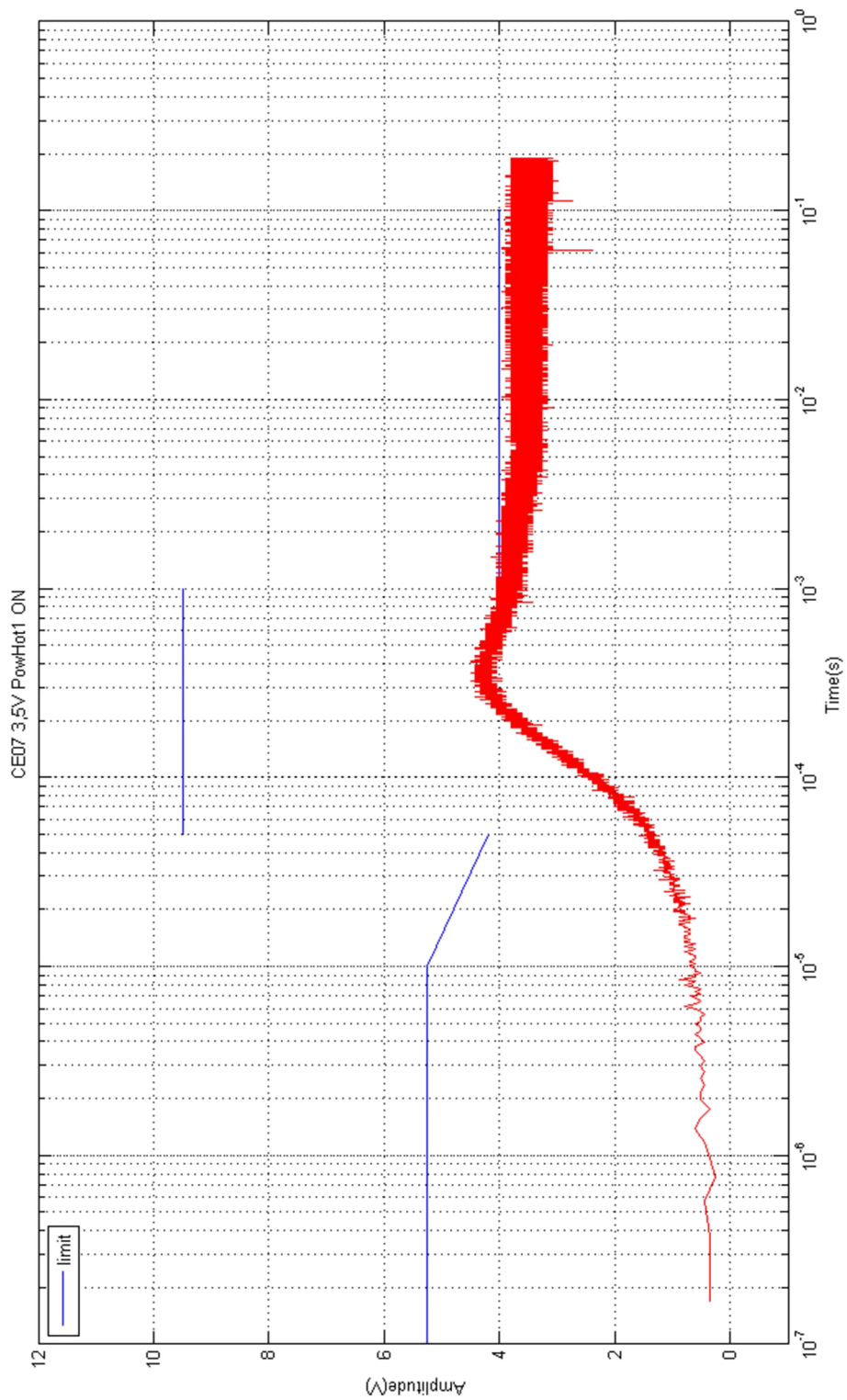


Fig. 18: power-on waveform for V_1 - V_2 on +3.5V_A/P_1 <hot> line.

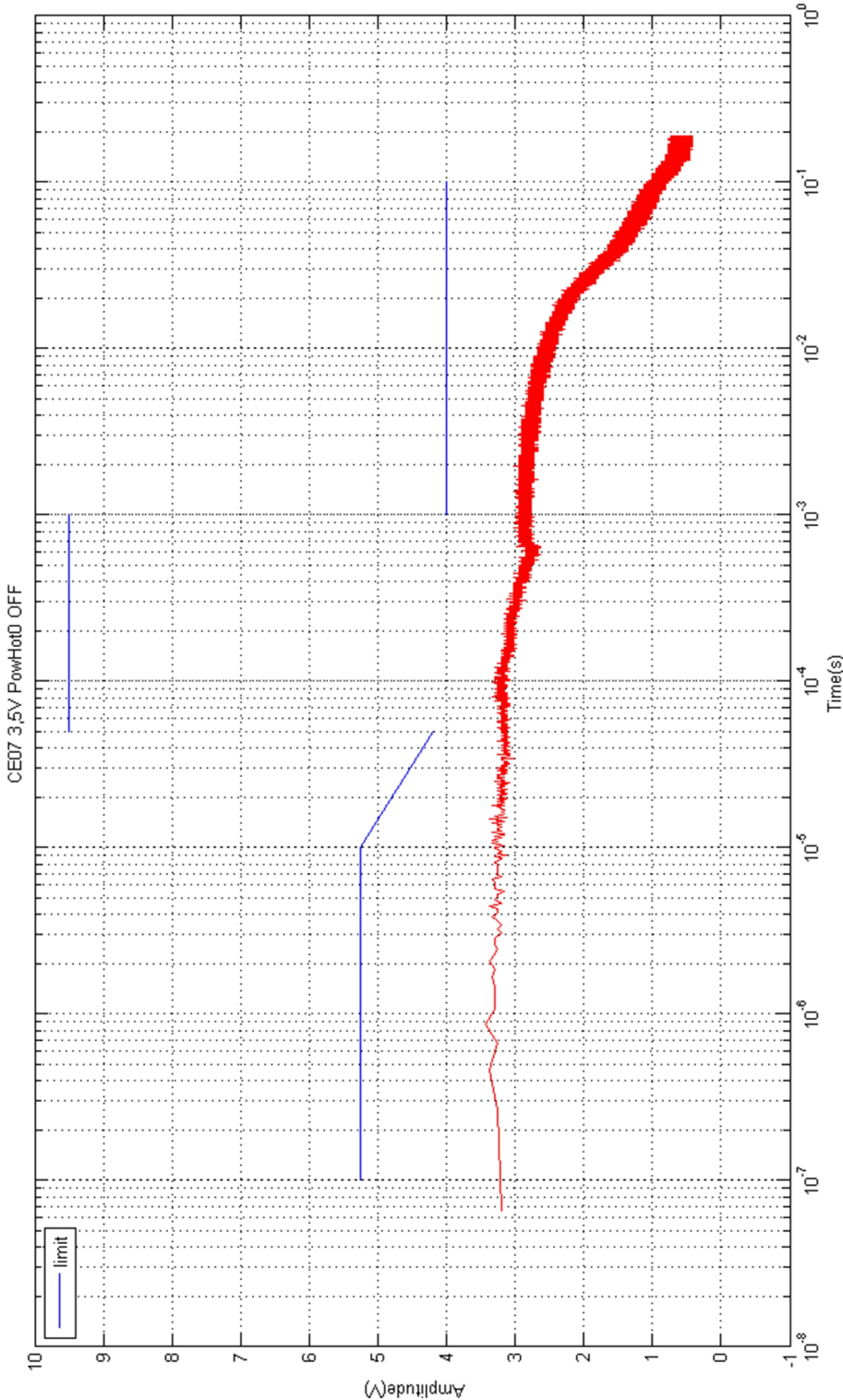


Fig. 19: power-off waveform for V₁-V₂ on +3.5V_{A/P_0} <hot> line.

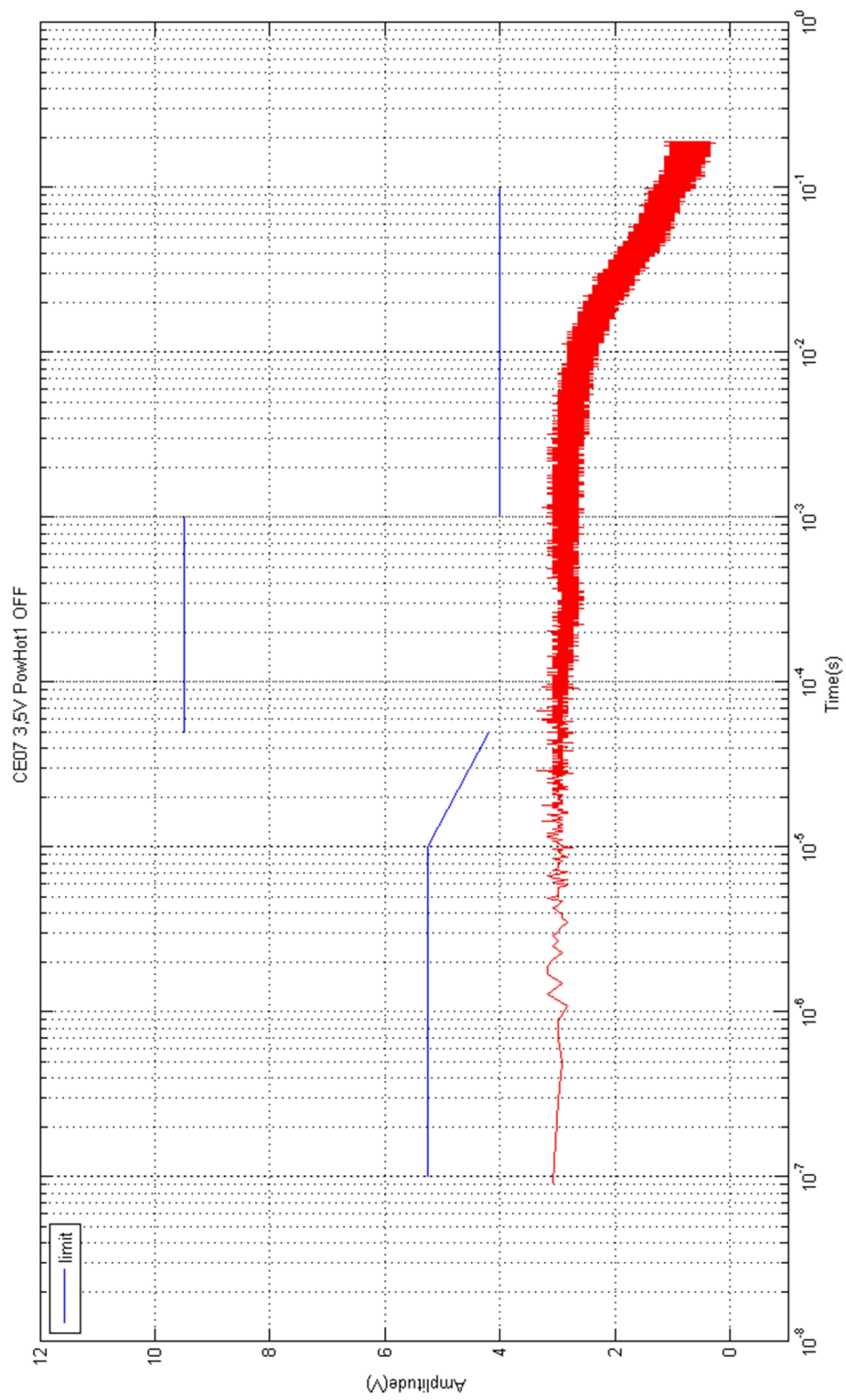


Fig. 20: power-off waveform for V_1 - V_2 on +3.5V_A/P_1 <hot> line.

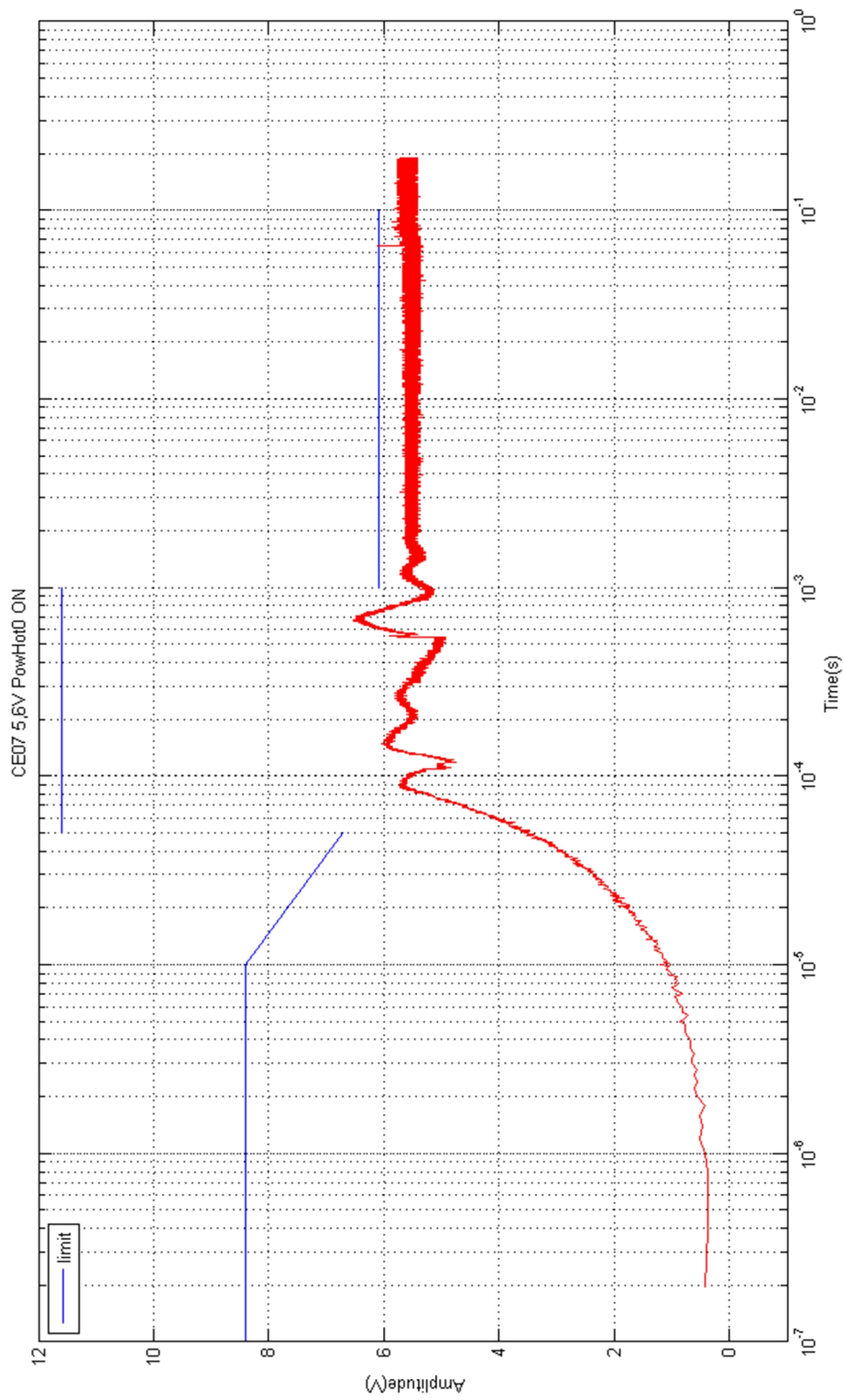


Fig. 21: power-on waveform for V₁-V₂ on +5.6V_{A/P_0} <hot> line.

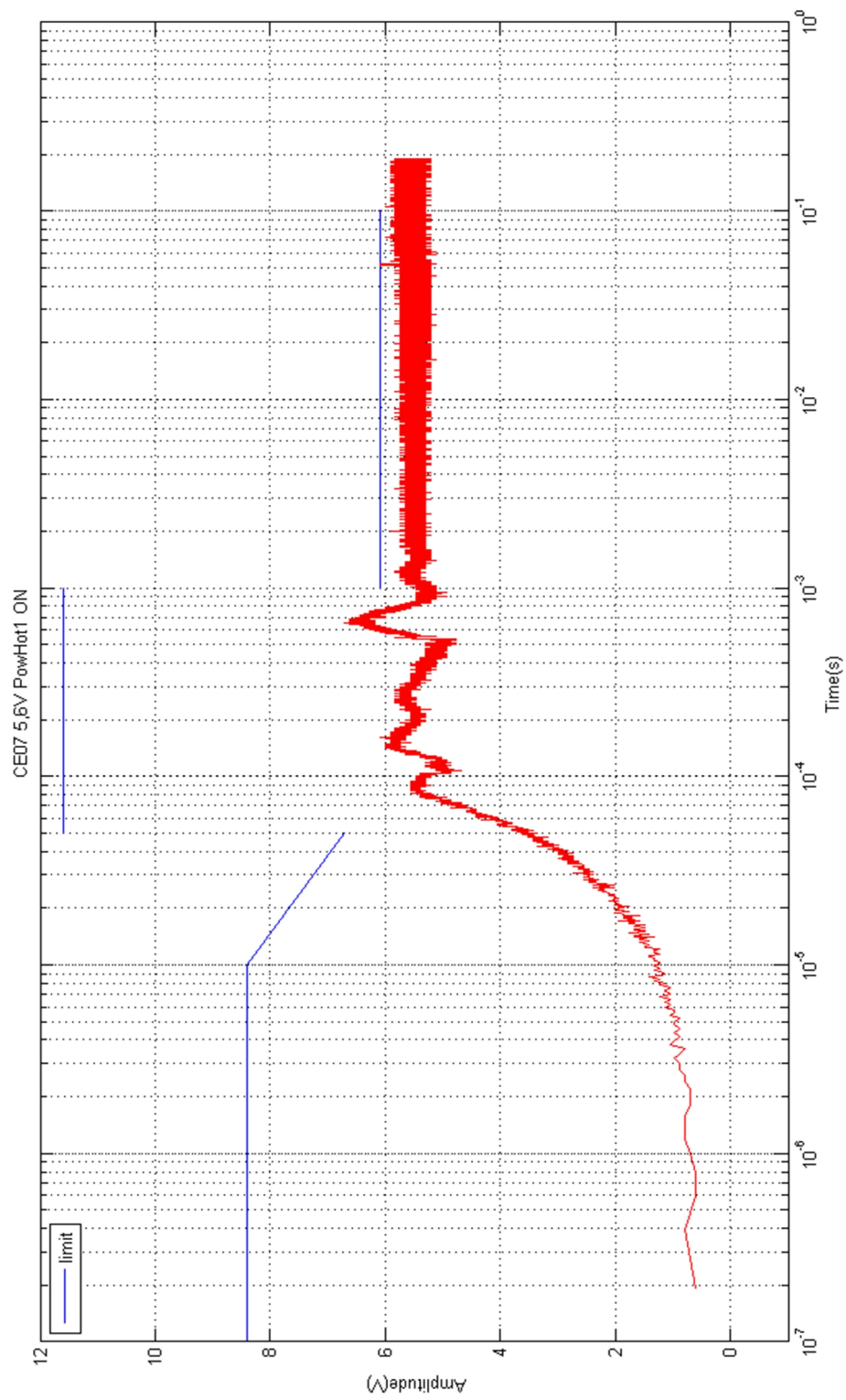


Fig. 22: power-on waveform for V_1 - V_2 on +5.6V_A/P_1 <hot> line.

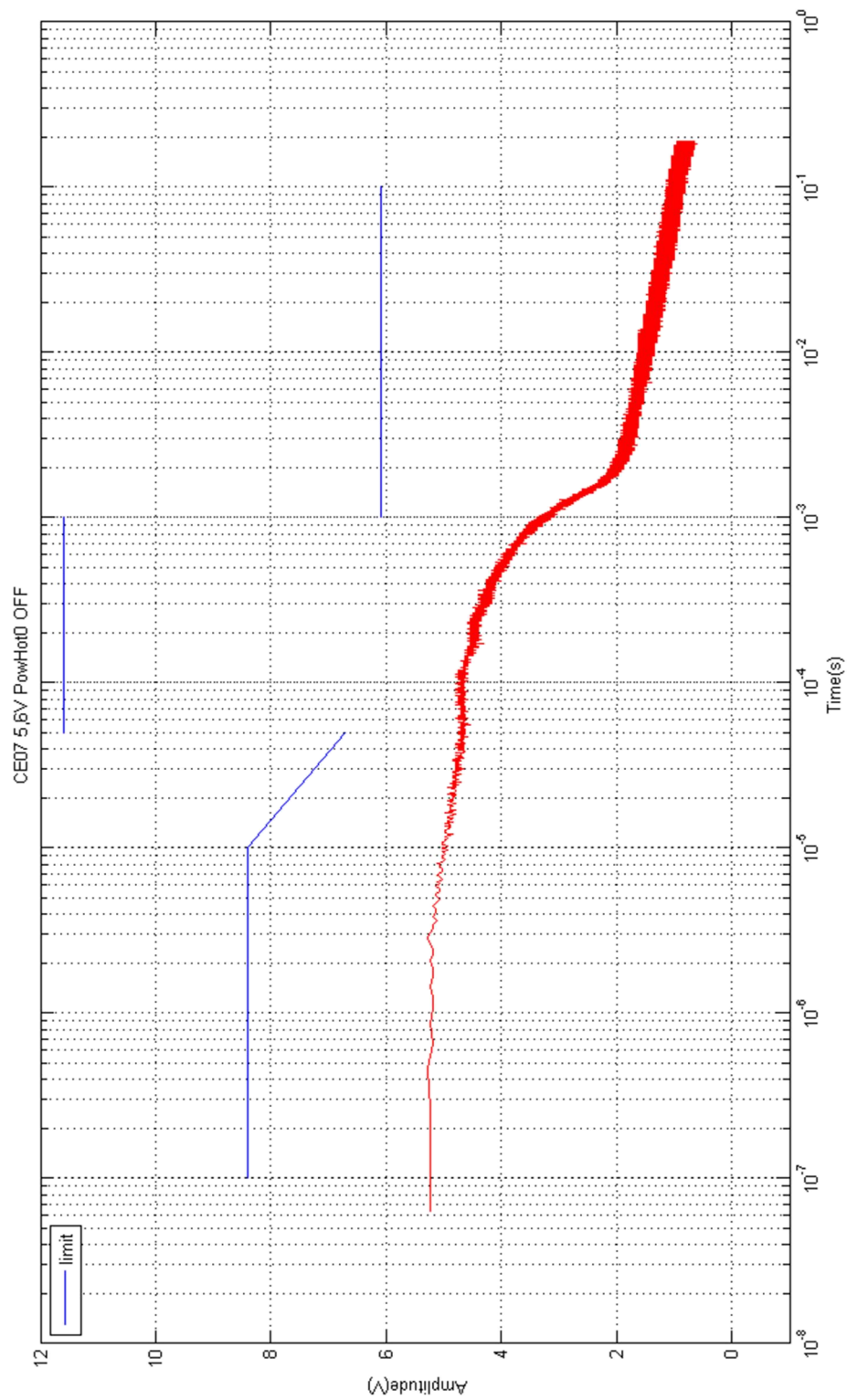


Fig. 23: power-off waveform for V_1-V_2 on $+5.6V_{A/P_0} <hot>$ line.

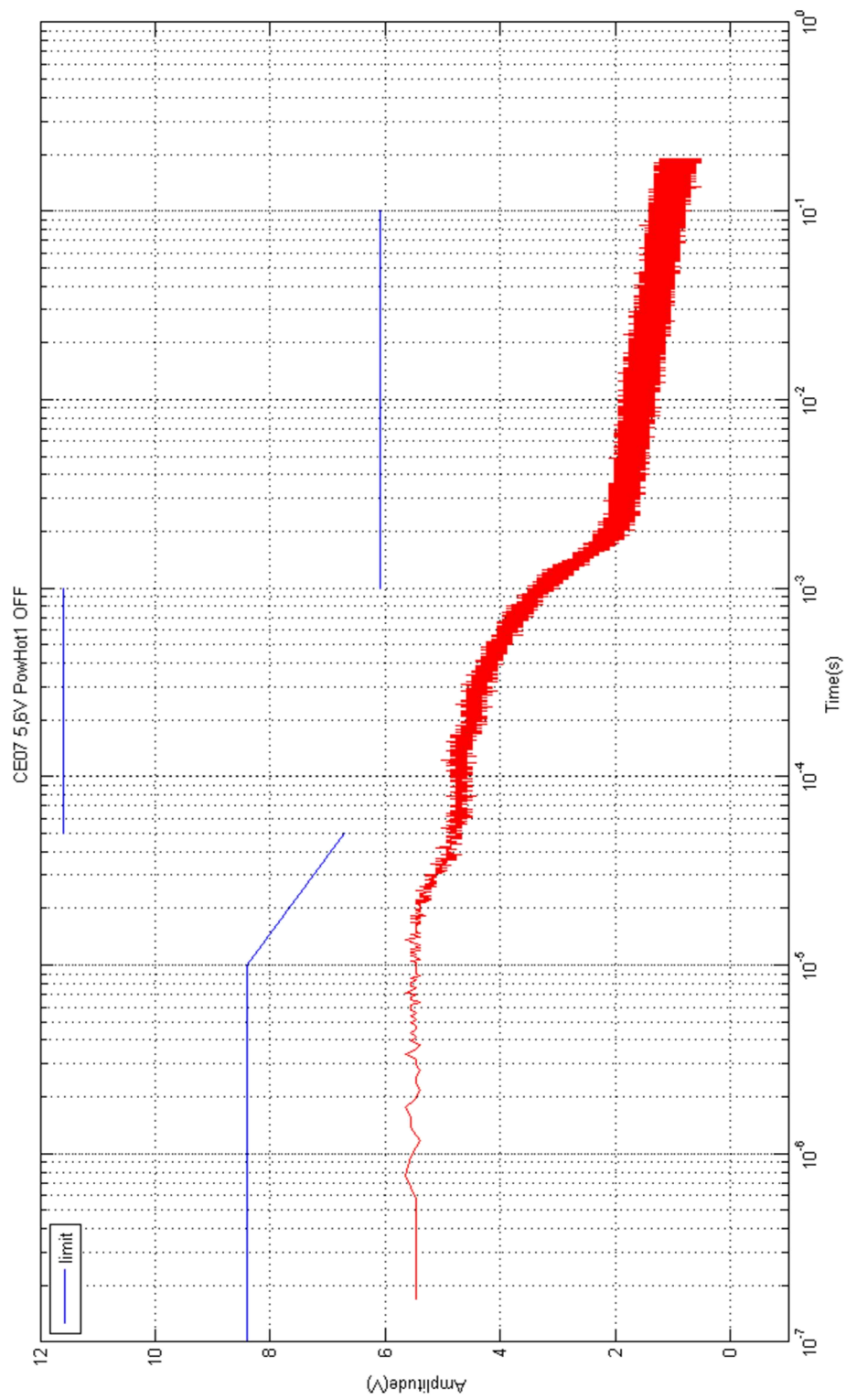


Fig. 24: power-off waveform for V_1-V_2 on $+5.6V_{A/P_1}$ line.

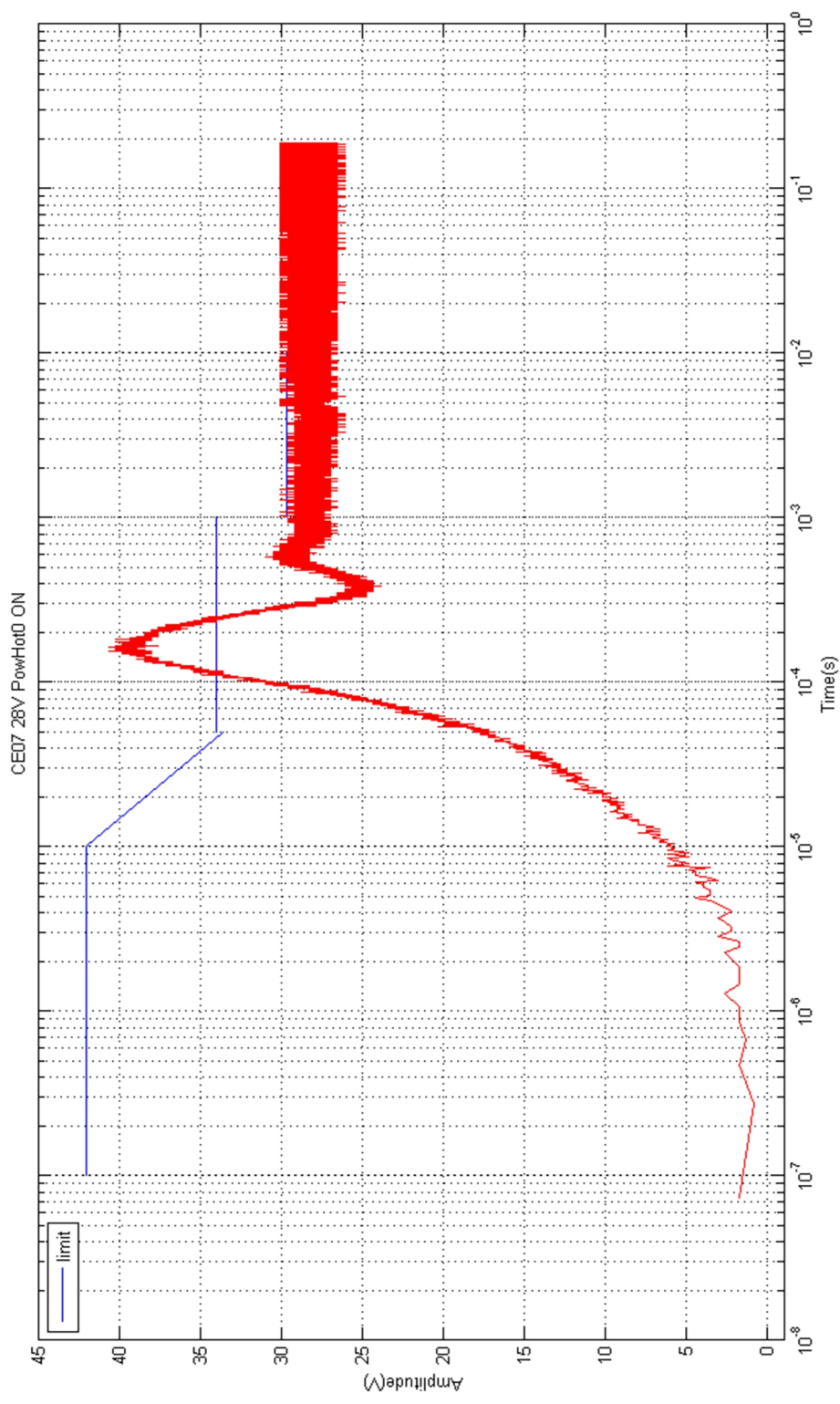


Fig. 25: power-on waveform for V_1 - V_2 on +28V $P_0 < \text{hot} >$ line.

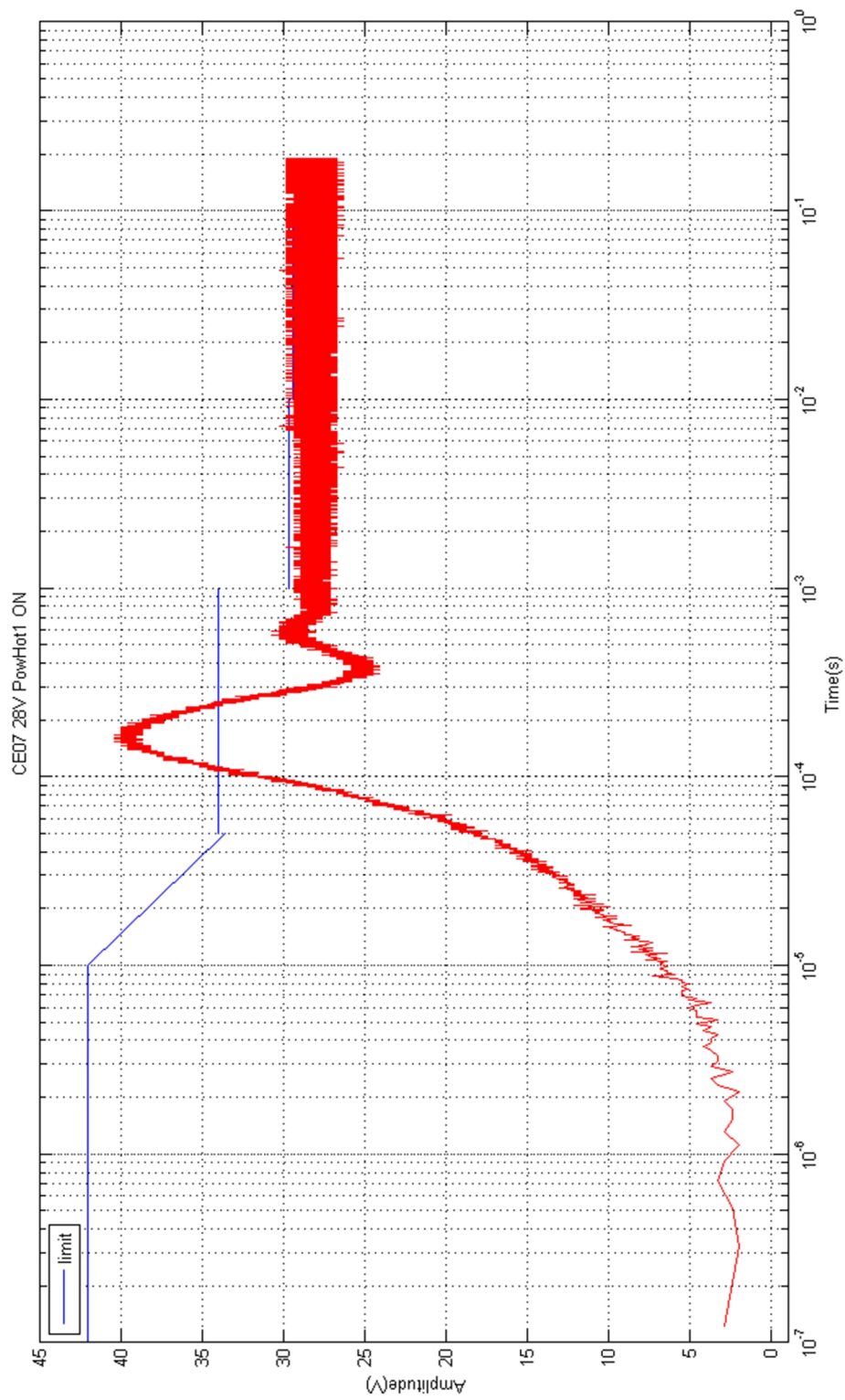


Fig. 26: power-on waveform for V₁-V₂ on +28V P₁ <hot> line.

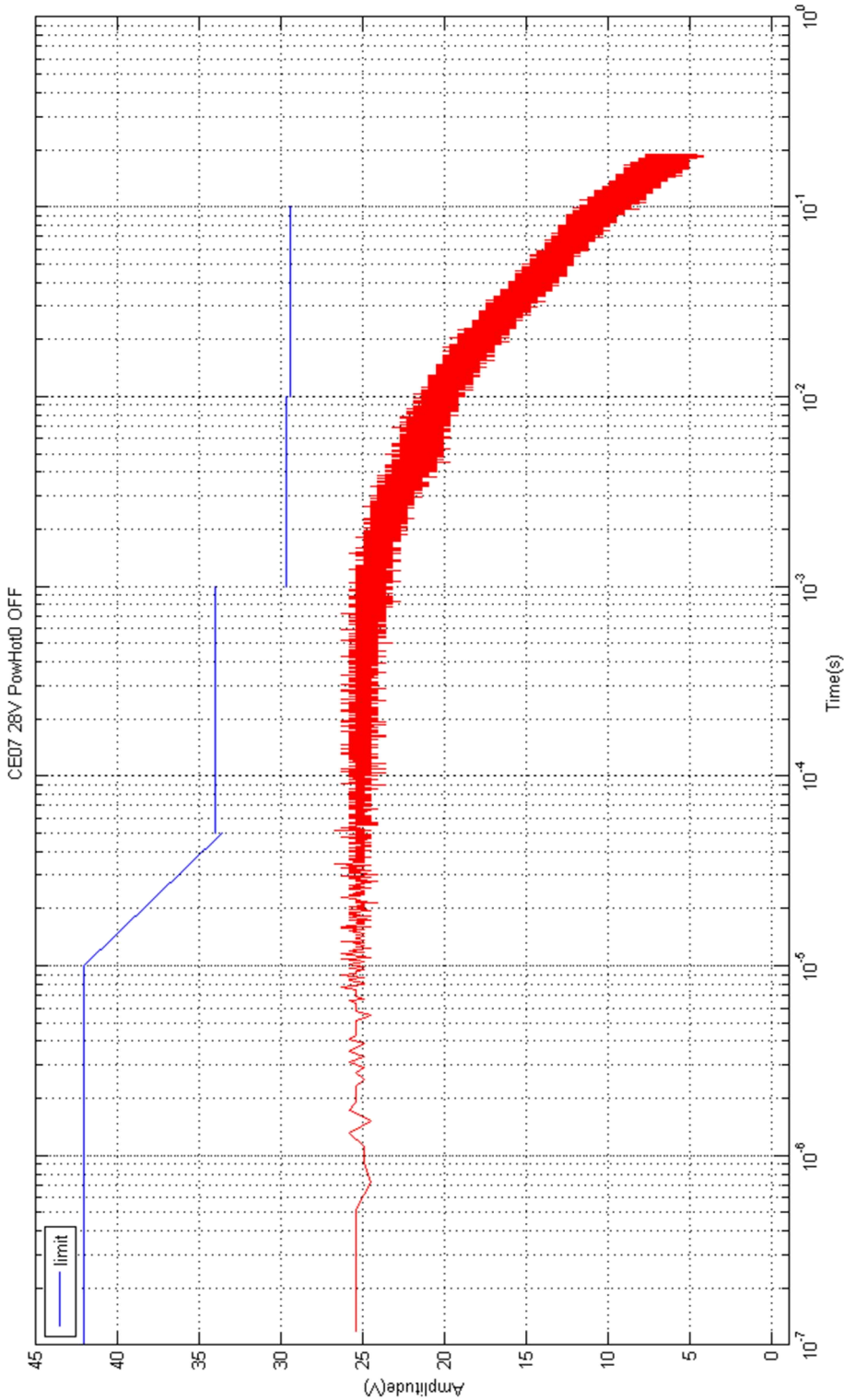


Fig. 27: power-off waveform for V₁-V₂ on +28V P₀ <hot> line.

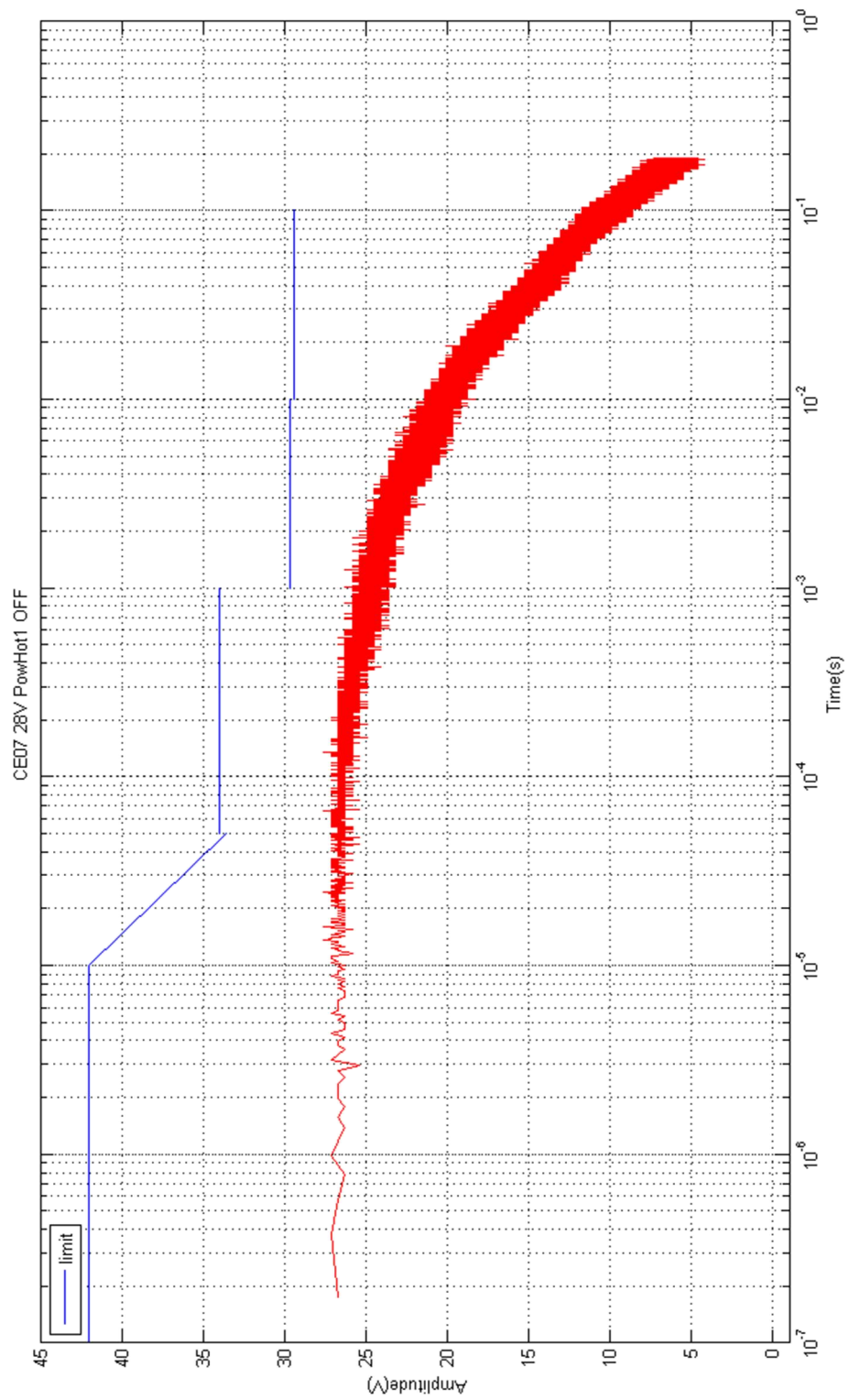


Fig. 28: power-off waveform for V_1 - V_2 on +28V P_1 <hot> line.

6. CS0, CS02, CS06 tests

6.1. General notes

The voltage injection spectrum has been derived, for each line under test, by adopting the levels given in [2.1] and limiting the voltage range to the admitted voltage range for HV Box for correct operation. To apply the spectrum thus obtained, the frequency range has been divided into intervals; each frequency interval is swept while a constant voltage value is applied; the voltage has been conservatively determined such as to be higher or equal to any required voltage value for that frequency interval.

A non-conformity has to be reported, concerning the fact that during conducted susceptibility tests CS01, CS02 and CS06, the injected voltages cover the admitted operating voltage ranges defined for HV Box, but not the generic requirements of [2.1], to avoid overstressing the HV box input circuitry. This non-conformity has been accepted by ASI and JAXA.

6.2. CS01 test

The configuration implemented for this test is shown in Fig. 29. The isolation transformer is applied only to the line under test. Note that each input power line is formed by two wires: the wires are short-circuited at the isolation transformer output.

Tab. 5 and Fig. 30 show the voltage injection spectrum to be applied on the power line under test; the applied voltage injection spectrum is verified by means of the oscilloscope. The applied maximum sweep speed for each frequency interval is also specified in Tab. 5.

Tab. 5: voltage injection spectrum for CS01 test.

frequency interval		maximum sweep speed (Hz/s)	minimum sweep duration (s)	amplitude (V, peak-to-peak)		
f_{\min} (Hz)	f_{\max} (Hz)			+3.5V	+5.6V	+28V
30	50	0.9	22	0.40	0.56	2.80
50	100	1.5	33	0.40	0.56	2.80
100	200	3	33	0.40	0.56	2.80
200	500	6	50	0.40	0.56	2.80
500	1k	15	33	0.40	0.56	2.80
1k	2k	30	33	0.40	0.56	2.80
2k	5k	60	50	0.40	0.56	2.80
5k	10k	150	33	0.31	0.43	2.16
10k	20k	300	33	0.24	0.34	1.68
20k	50k	600	50	0.16	0.24	1.20

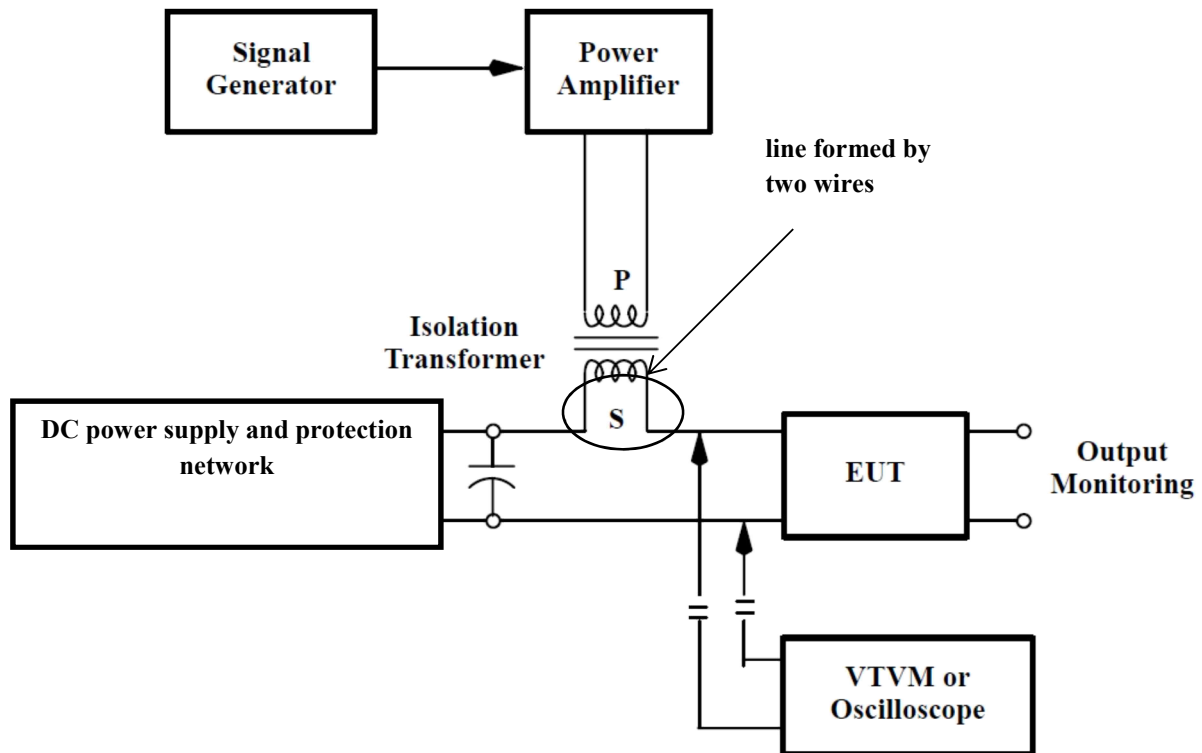
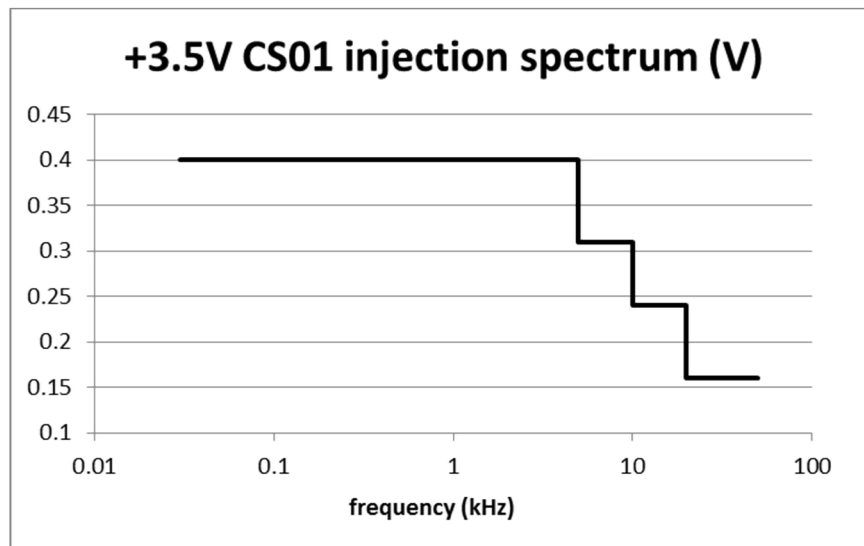
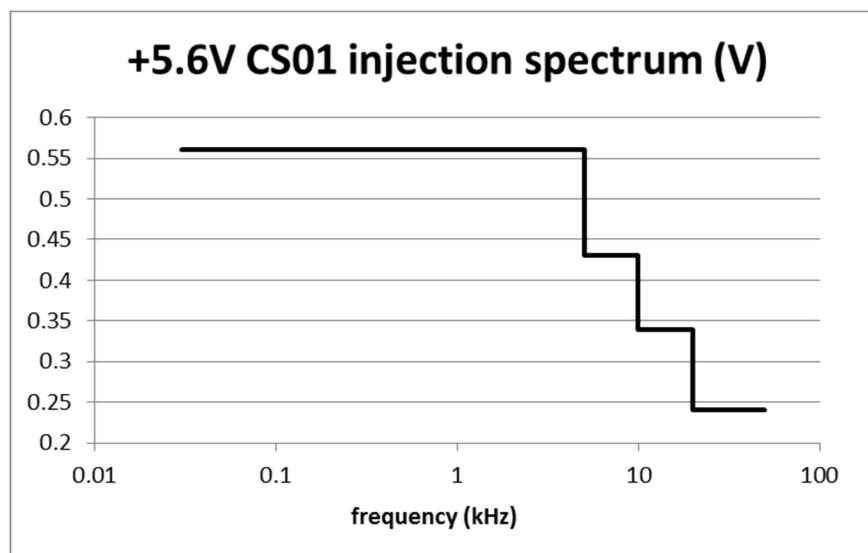


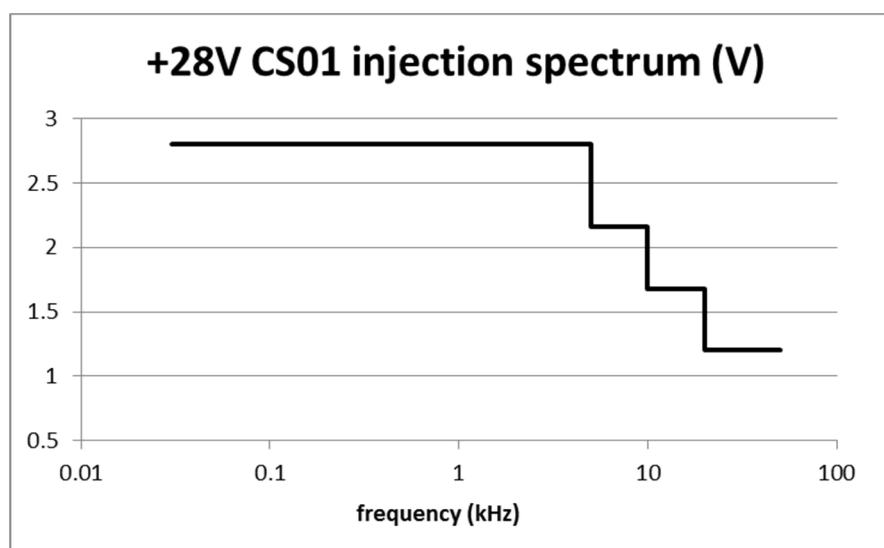
Fig. 29: test set-up configuration for CS01 test of a generic power line under test of HV Box. EUT is the HV Box.



(a)



(b)



(c)

Fig. 30 (a)-(c): voltage injection spectrum for CS01 test.

6.3. CS02 test

The configuration implemented for this test is shown in Fig. 31. The coupling capacitor is applied only to the line under test. The value of the coupling capacitor is > 600 nF.

Note that each input power line is formed by two wires; the wires are short-circuited within 5 cm from the connector on the HV Box, where the coupling capacitor and read-out instrument (oscilloscope etc.) are applied; the DC voltage on this node is also monitored.

Tab. 6 describes the voltage injection spectrum to be applied on the line under test; the applied voltage injection spectrum is verified by means of the oscilloscope/interference analyzer. For each input power line under test, the specified voltage spectrum is injected while a continuous functional/electrical test is performed. Before and after the frequency sweep, other functional/electrical tests are performed.

No susceptibility is found in the apparatus, for the line under test, if the functional/electrical test is fully passed. Otherwise, the input injection level is decreased to determine and record the susceptibility threshold level for the line under test.

Tab. 6: voltage injection spectrum for CS02 test.

frequency interval		maximum sweep speed (Hz/s)	minimum sweep duration (s)	amplitude (V, peak-to-peak) for each line		
f_{\min} (Hz)	f_{\max} (Hz)			+3.5V	+5.6V	+28V
50k	100k	1.5k	33	0.40	0.56	2.80
100k	200k	3k	33	0.40	0.56	2.80
200k	500k	6k	50	0.40	0.56	2.80
500k	1M	15k	33	0.40	0.56	2.80
1M	2M	30k	33	0.40	0.56	2.80
2M	5M	60k	50	0.40	0.56	2.80
5M	10M	150k	33	0.40	0.56	2.80
10M	20M	300k	33	0.40	0.56	2.80
20M	50M	600k	50	0.40	0.56	2.80

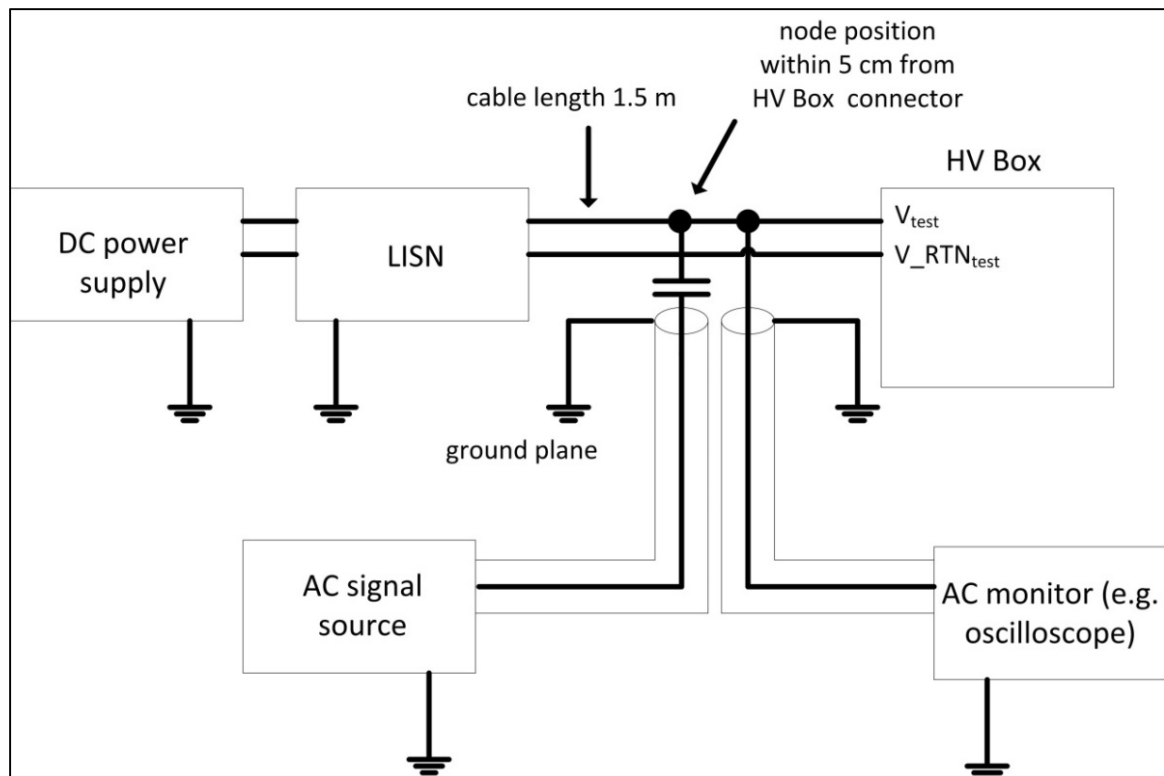


Fig. 31: test set-up configuration for CS02 test of a generic power line of HV Box.

6.4. CS06 test

The configuration implemented for this test is shown in Fig. 32. Note that each input power line is formed by two wires; the wires are short-circuited in the vicinity of the connector on the HV Box, where the spike generator and read-out instrument (oscilloscope) are connected; the DC voltage on this node is also monitored.

During the test, each of four different spike signals (see Tab. 7 and Fig. 33) is repeatedly applied by the spike generator, superimposed on the DC voltage, to the line under test, with a required repetition rate between 6 and 10 Hz each (actually set at 8 Hz), while a continuous functional/electrical test is performed at least for 2 minutes per spike. Before and after the different spikes are applied, other functional/electrical tests are performed.

An oscilloscope check is performed to assure that the waveforms at the input terminals of the HV Box are consistent with what specified. The applied spike waveform and repetition rate are recorded.

No susceptibility is found in the apparatus for the line under test, if the functional/electrical test is fully passed. Otherwise, the spike amplitude is decreased to determine and record the susceptibility threshold level for the line under test. The repetition rate of the functional/electrical anomaly found is also recorded, if applicable.

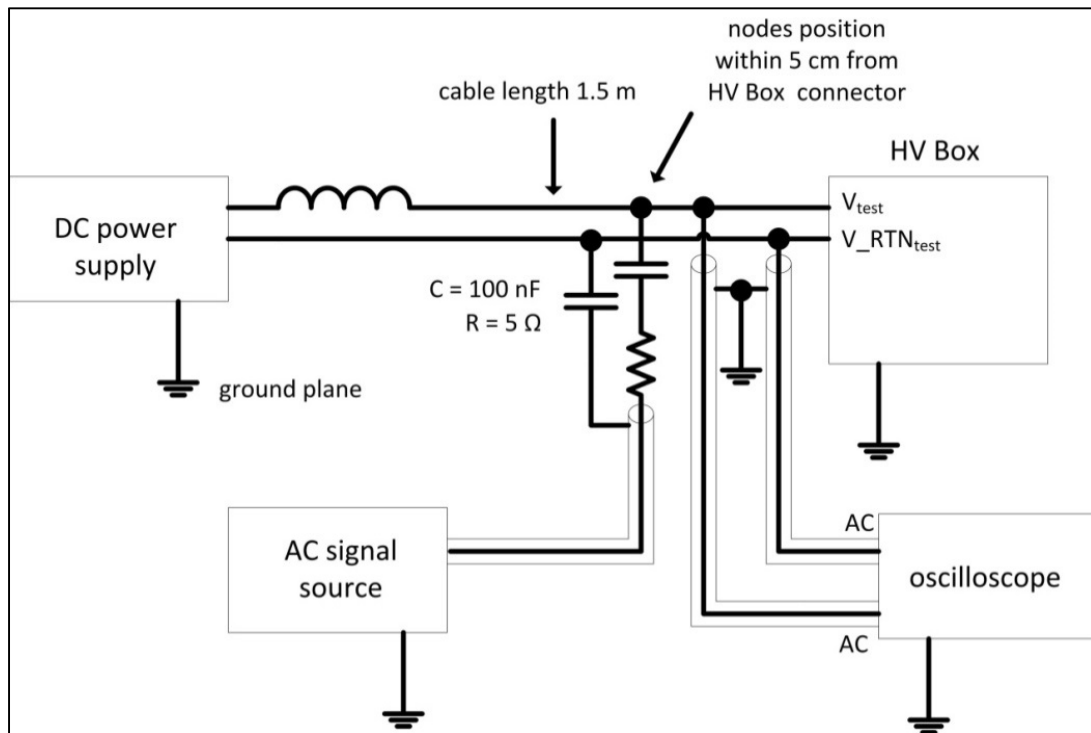


Fig. 32: test set-up configuration for CS06 test of a generic line under test of HV Box. EUT is the HV Box. The spike is applied through a non-inductive 5 Ω resistor.

Tab. 7: amplitude and pulse-width of injected spikes, at the input terminals of the HV Box, for CS06 test.

SPIKE A	line	+3.5V	+5.6V	+28V
	amplitude E (V)	+0.20	+0.28	+1.40
	pulse-width $t = (10 \pm 2) \mu s$			
SPIKE B	same as A, with opposite polarity			
SPIKE C	line	+3.5V	+5.6V	+28V
	amplitude E (V)	+0.20	+0.28	+1.40
	pulse-width $t = (0.15 \pm 0.03) \mu s$			
SPIKE D	same as C, with opposite polarity			

6.5. Employed equipment (CS01, CS02, CS06 tests)

- AC signal generator: WAVETEK MODEL 166, S.N. T93092032.
- AC signal generator (used for CS06 test, power injection on 28V line): Hewlett-Packard 214A. S.N. 611-00616.
- DC power supplies ($V_{3.5V}$, $V_{5.6V}$, V_{28V}), current meters ($I_{3.5V}$, $I_{5.6V}$, I_{28V}):
 - Agilent U8032A. S/N MY52180017. Calibration expiry date 2013-05-03.
 - TTI QL355T. S.N. 346658. Current meter cross-calibrated with Agilent U8032A.
- AC monitor ($V_{3.5V}$, $V_{5.6V}$, V_{28V}): Lecroy Waverunner 6100A oscilloscope. S.N. LCRY0604P16335. Calibration expiry date: 2013-07-12.
- AC monitor: Agilent DSO6054A oscilloscope (4 channels). S.N. MY44006050. Cross-calibrated with Lecroy Waverunner 6100A oscilloscope.
- DC voltage meter ($V_{3.5V}$, $V_{5.6V}$, V_{28V} , V_{DC_MON}): Agilent 34401A. S/N MY47003362. Calibration expiry date 2013-11-05.

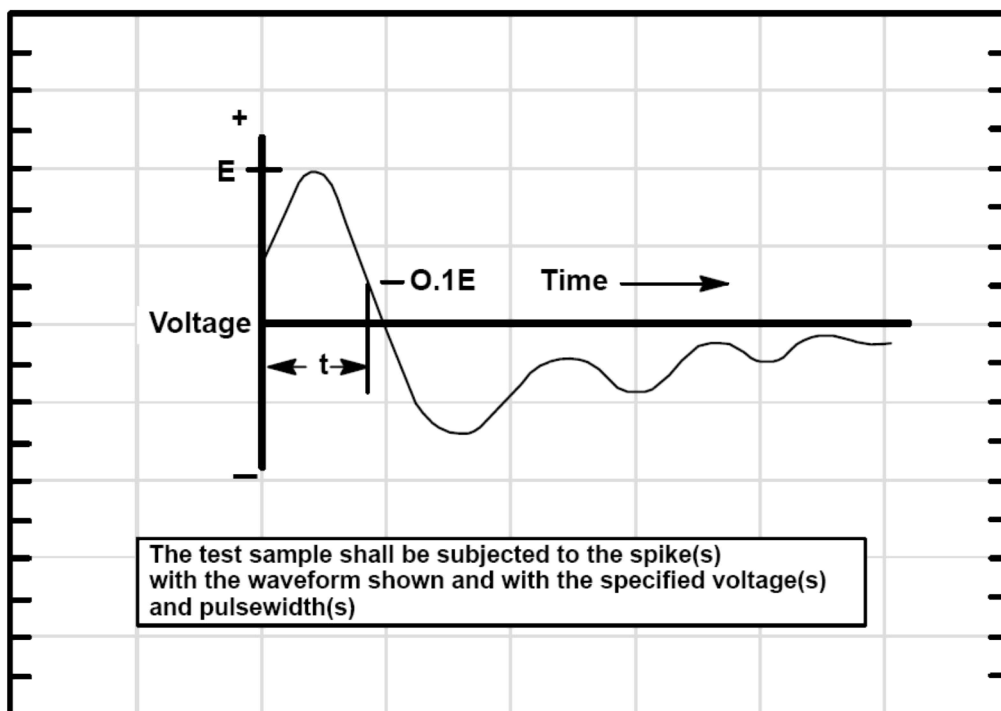


Fig. 33: injected spike waveform for CS06 test.

7. RE02 test

7.1. Configuration (RE02 test)

The test configuration is shown in Fig. 34. Power is brought to inputs by means of 3 m long (2 m long inside the chamber), AWG 24, non-twisted, non-shielded pairs of wires. Digital lines from MDC emulator are brought by means of 3 m long (2 m long inside the chamber), AWG 26, twisted, non-shielded pairs of wires.

Power supplies, MDC emulator system, interference analyzer are placed outside the chamber. The test antenna is set 1 m apart from the HV Box side; no parts of the antennas are located at less than 30 cm from the floor and ceiling and at less than 1 meter from the walls of the chamber. In the frequency range above 30 MHz, linearly polarized antennas are positioned so as to make both vertical and horizontal measurements.

The interference analyzer is set into peak detector mode. Tab. 8 reports the applied 3 dB filter bandwidth, total sweep time, and number of sweeps which are averaged to give the final result, for each frequency interval.

The RE02 test is passed if the limits in Tab. 9 (shown also in Fig. 35) are not exceeded with the antenna placed at the required test distance of 1 m.

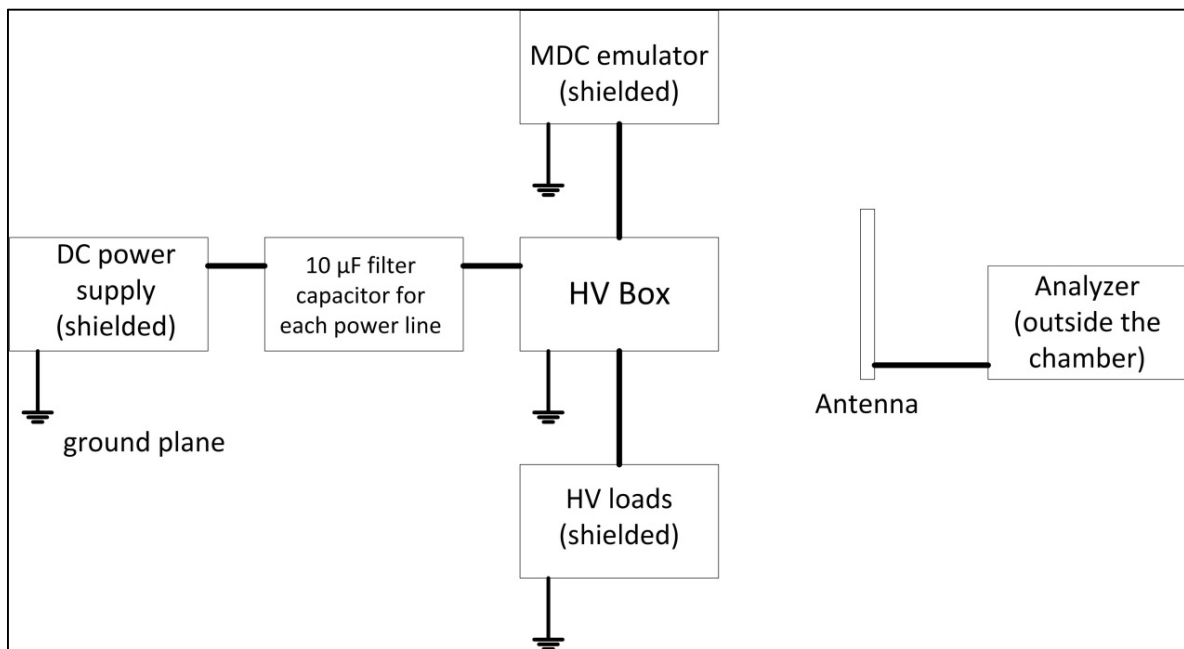


Fig. 34: test set-up configuration for RE02 test.

Tab. 8: configuration of interference analyzer.

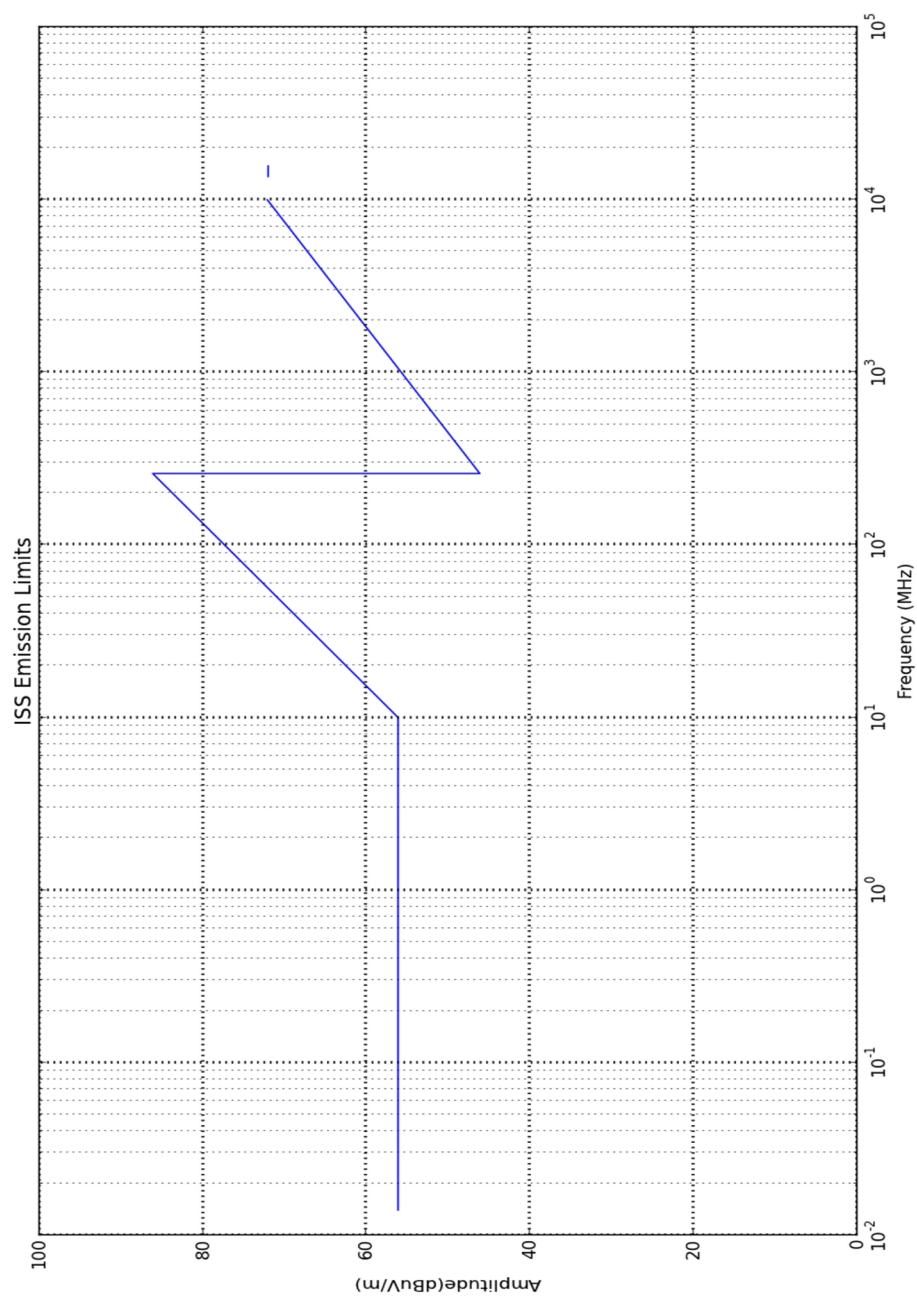
frequency range	3 dB filter bandwidth	total sweep time (s)	number of sweeps (averaged)
14 kHz - 150 kHz	1 kHz	5	10
150 kHz - 30 MHz	10 kHz	60	5
30 MHz - 200 MHz	100 kHz	30	5
200 MHz - 1 GHz	100 kHz	1	10
1 GHz - 4 GHz	3 kHz	1000	1
4 GHz - 7 GHz	3 kHz	1000	1
7 GHz - 11 GHz	100 Hz	3000	1
11 GHz - 15.5 GHz	100 Hz	3000	1

Tab. 9: emission limits for RE02 test.

Frequency	RE02 emission limits (peak)
14 kHz – 10 MHz	56 dBµV/m
10 MHz – 259 MHz	Increasing log linearly with increasing frequency from 56 to 86 dBµV/m (16 dB per decade)
259 MHz – 10 GHz	Increasing log linearly with increasing frequency from 46 to 72 dBµV/m (16 dB per decade)
13.5 – 15.5 GHz	72 dBµV/m

Tab. 10: combinations of analyzers and antennae for RE02 test. (*) means that A_1 is set in “receiver mode” (for better noise performances).

Frequency	Analyzer	Antenna
14 kHz – 30 MHz	A_1	AN_1
30 MHz – 200 MHz	A_1	AN_2
200 MHz – 1 GHz	$A_1(*)$	AN_3
1 GHz – 7 GHz	$A_1(*)$	AN_4
7 GHz – 10 GHz	A_2	AN_4
13.5 GHz – 15.5 GHz	A_2	AN_4

**Fig. 35:** emission limits for RE02 test.

Employed equipment is listed below.

- Analyzers:
 - A₁. Rode&Schwarz ESPI7 EMI test receiver, frequency range 9 kHz - 7 GHz. S.N. 101141. Calibration expiry date: 2013-11-26.
 - A₂. Tektronix 492AP spectrum analyzer, frequency range 50 kHz - 21 GHz. S.N. B010121. Calibration expiry date: 2012-11-30. Cross-calibrated with Rode&Schwarz ESPI7 EMI test receiver.
- Antennae:
 - AN₁. Rode&Schwarz HFH2-Z1 rodantenna, frequency range 9 kHz -30 MHz. S.N. 335.3215.52.
 - AN₂. AILTECH 94455-1 biconical antenna, frequency range 20 MHz - 200 MHz. S.N. 833. Cross-calibrated in the frequency range 80 MHz - 200 MHz, by means of a known field generated with antenna AN_{cal} (voltage applied to AN_{cal} antenna has been monitored with A₁).
 - AN₃. Schwarzbeck VUSPL 9111, log-periodical antenna, frequency range 200 MHz - 4 GHz. S.N. 621. Cross-calibrated in the frequency range 200 MHz - 2.5 MHz, by means of a known field generated with antenna AN_{cal} (voltage applied to AN_{cal} antenna has been monitored with A₁).
 - AN₄. ARA DRG-118/A double ridged-horn antenna, frequency range 1 GHz - 18 GHz. S.N. 1379. Calibration expiry date 2013-10-20.
 - AN_{cal}. ARC PCD8250 biconical antenna, frequency range 80 MHz - 2.5 GHz. S.N. SN3131/02. Calibration expiry date 2013-10-19.
- Power supplies, current meters:
 - Agilent U8032A. S/N MY52180017. Calibration expiry date 2013-05-03.
 - TTi QL355T. S.N. 346658. Current meter cross-calibrated with Agilent U8032A.

Tab. 10 shows the employed combinations of analyzers and antennae for different frequency ranges. The attenuation factor of the cable, installed between antenna and analyzer, has been measured with Rode&Schwarz ESPI7 (set in “network analyzer” mode), as shown in Fig. 36. Antenna factors for listed antennae are shown in Fig. 37(a)-(c).

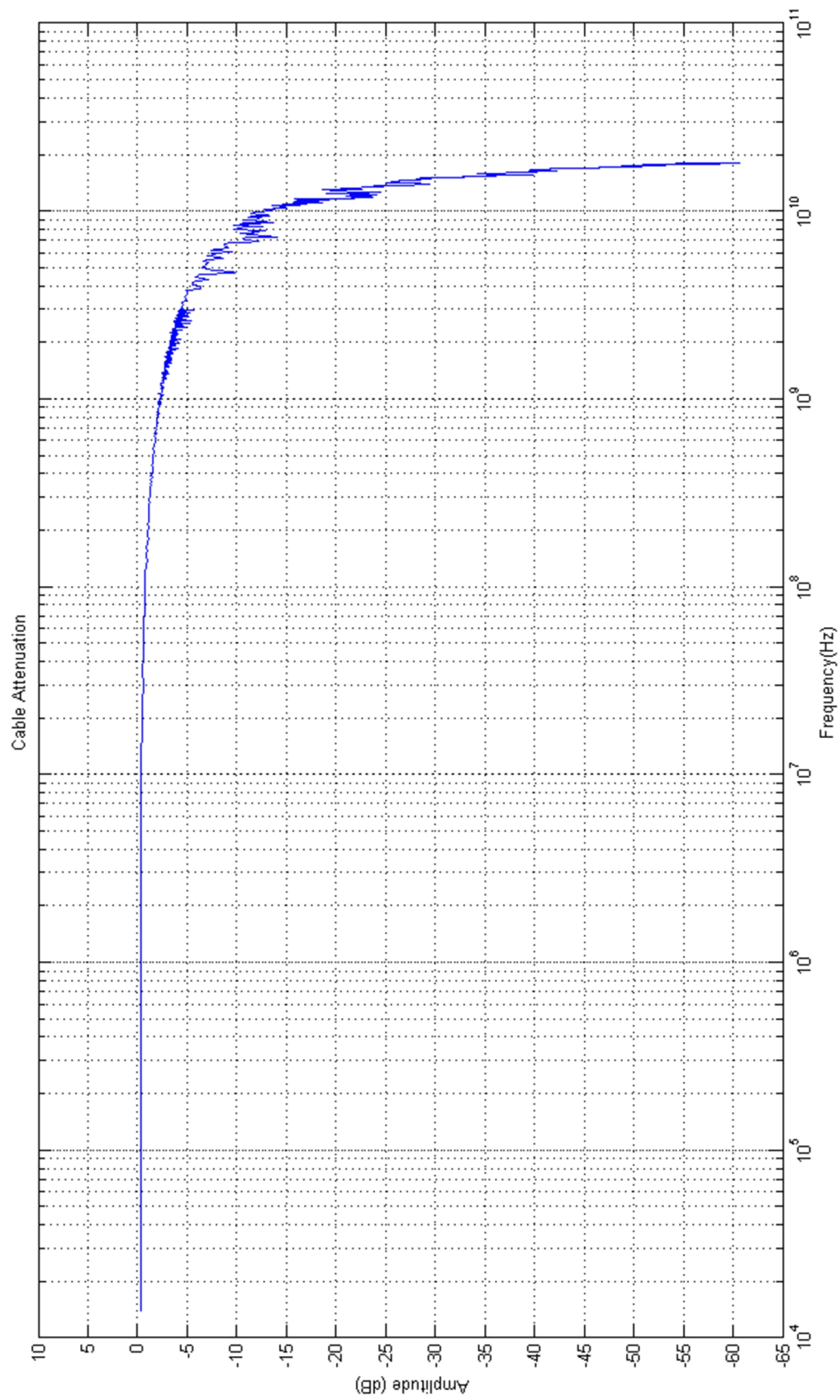


Fig. 36: attenuation factor of the cable installed between antenna and analyzer.

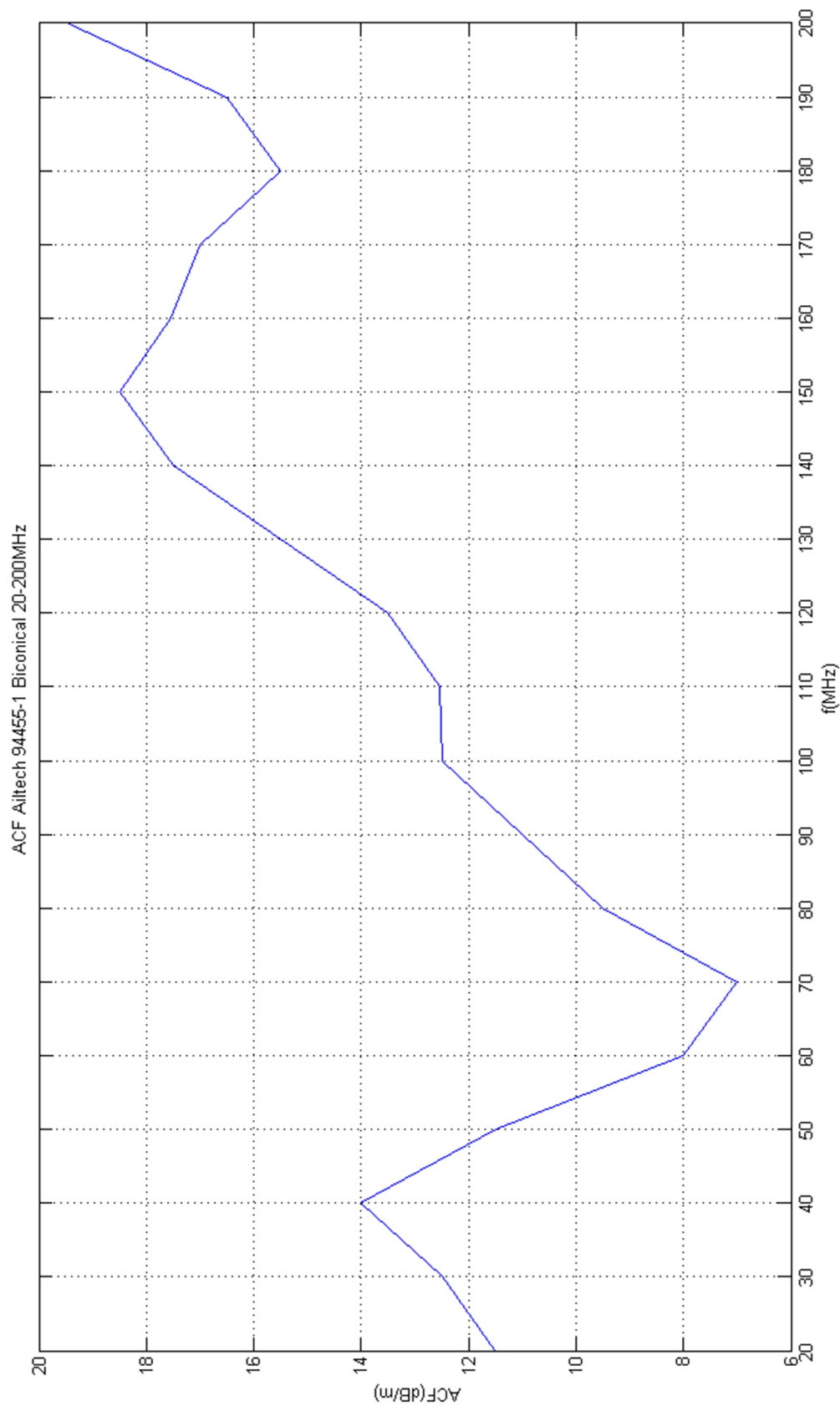


Fig. 37a

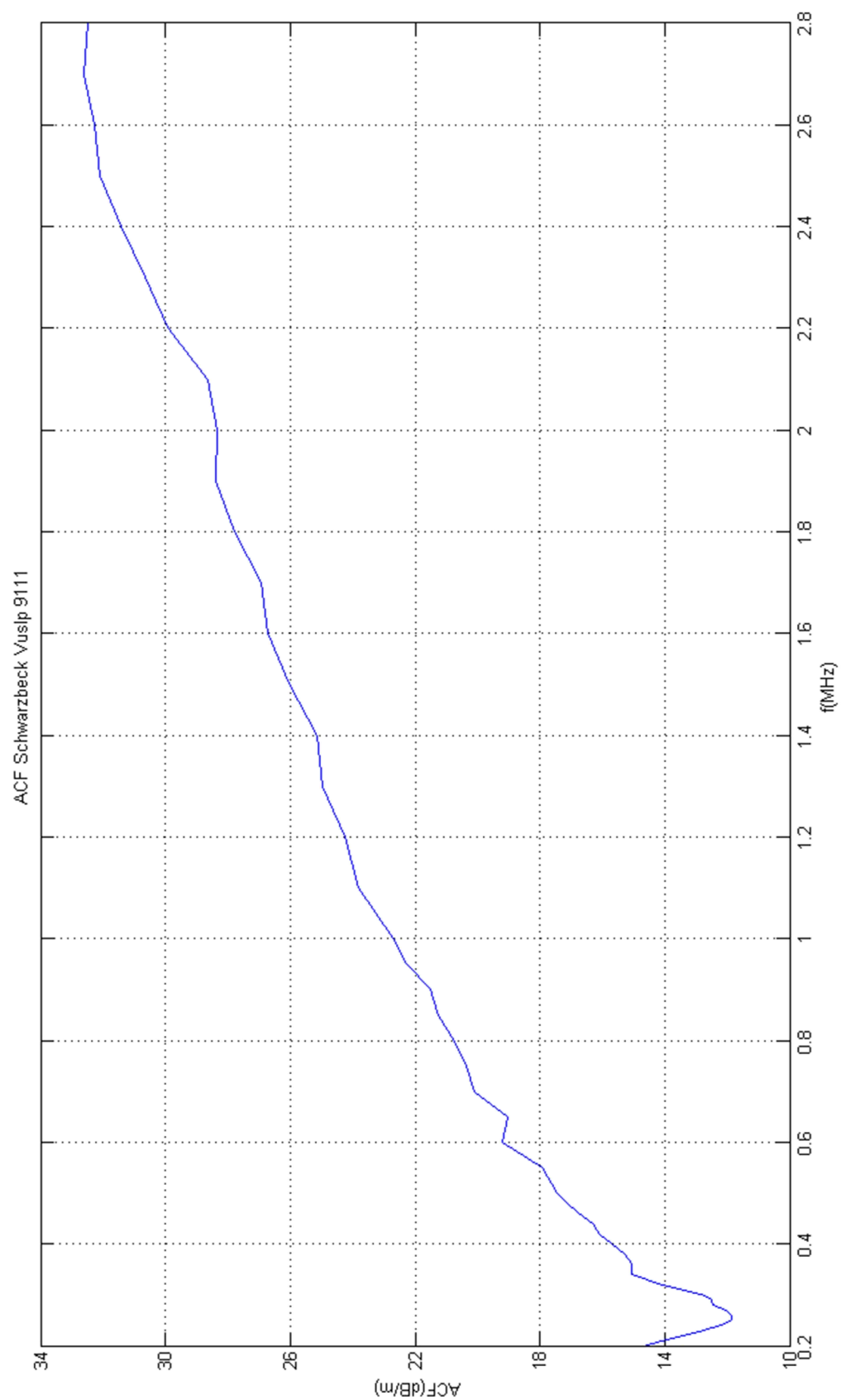


Fig. 37b

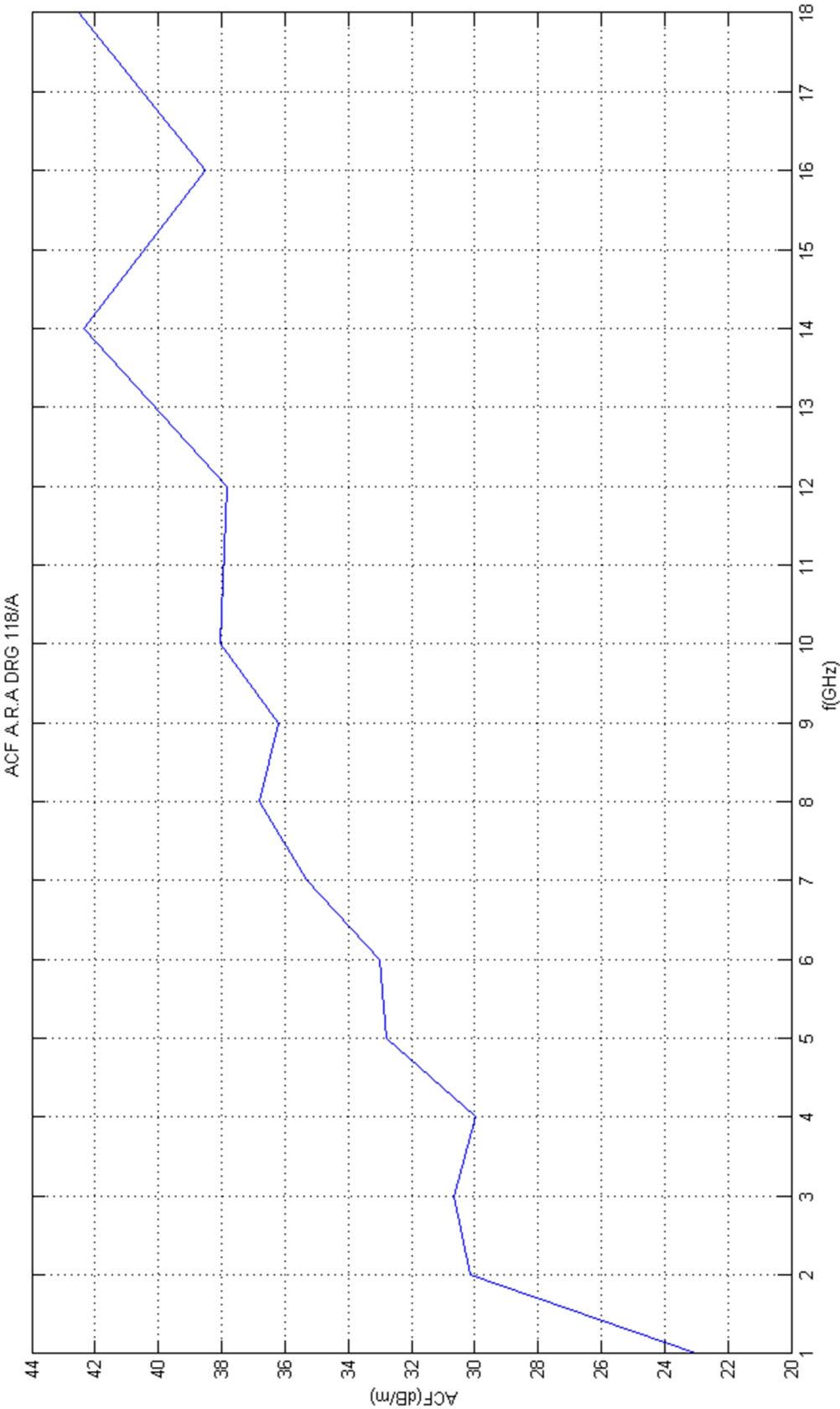


Fig. 37c

7.2. Results (RE02 test)

Measurements performed during RE02 test are shown in Figs. 38, 39 and 40, as described in what follows. Figs. 38(a)-(b) show the radiated emissions measured for the HV Box hot part for frequencies < 30 MHz. Applicable RE02 limit is also shown for comparison.

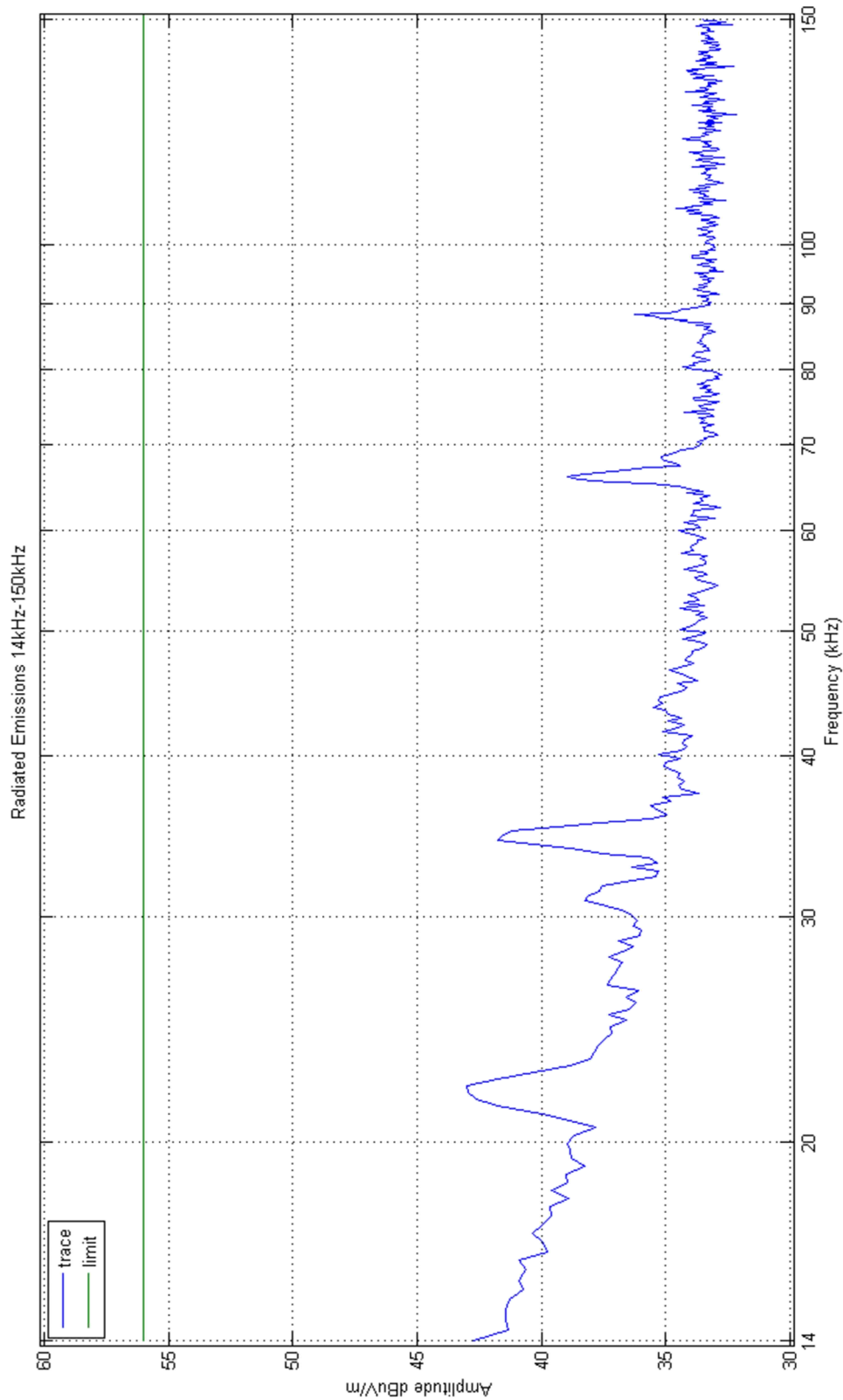


Fig. 38a

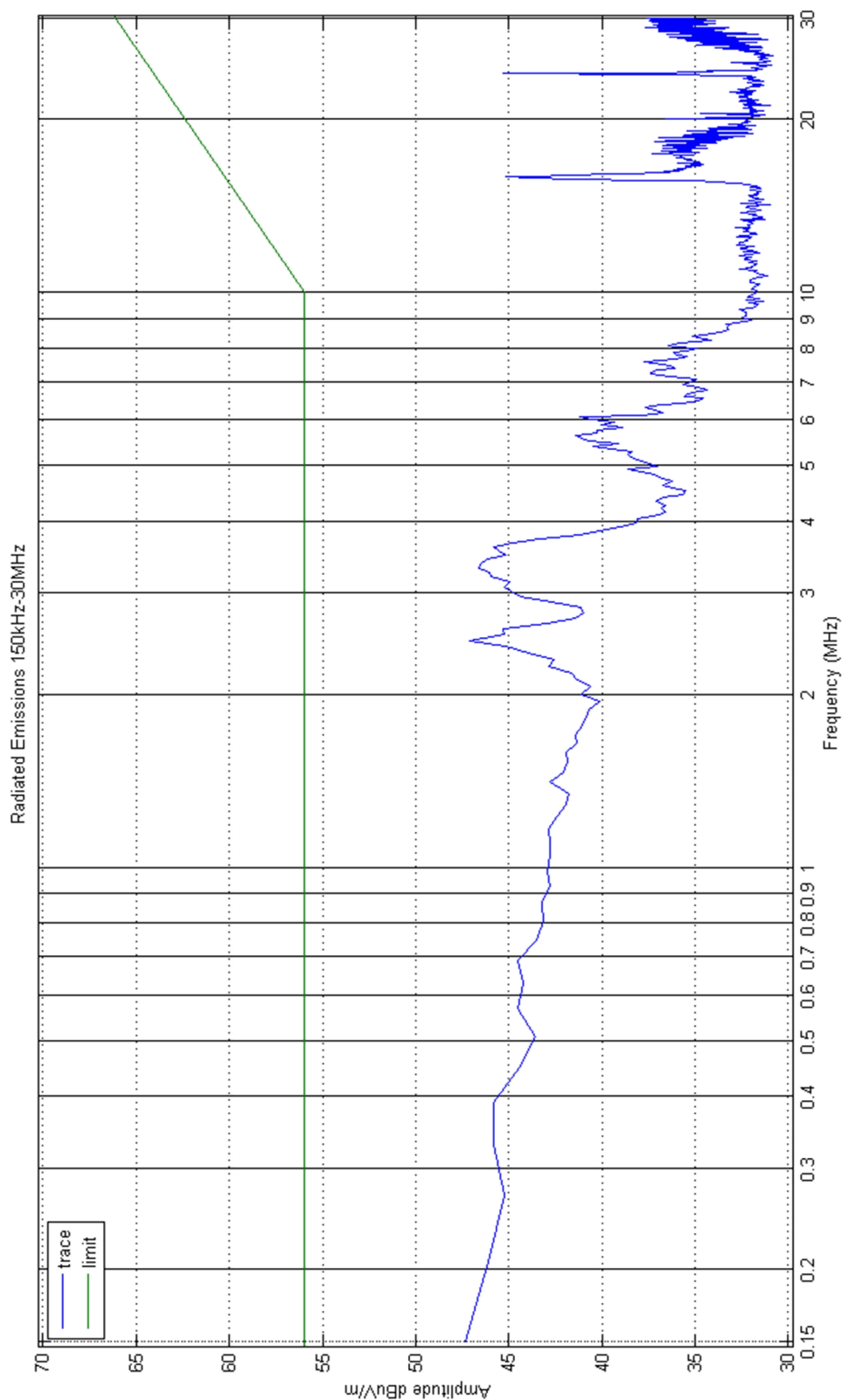


Fig. 38b

Figs. 39(a)-(f) show the radiated emissions measured for the HV Box hot part for frequencies > 30 MHz, with antenna directed horizontally. Applicable RE02 limit is also shown for comparison.

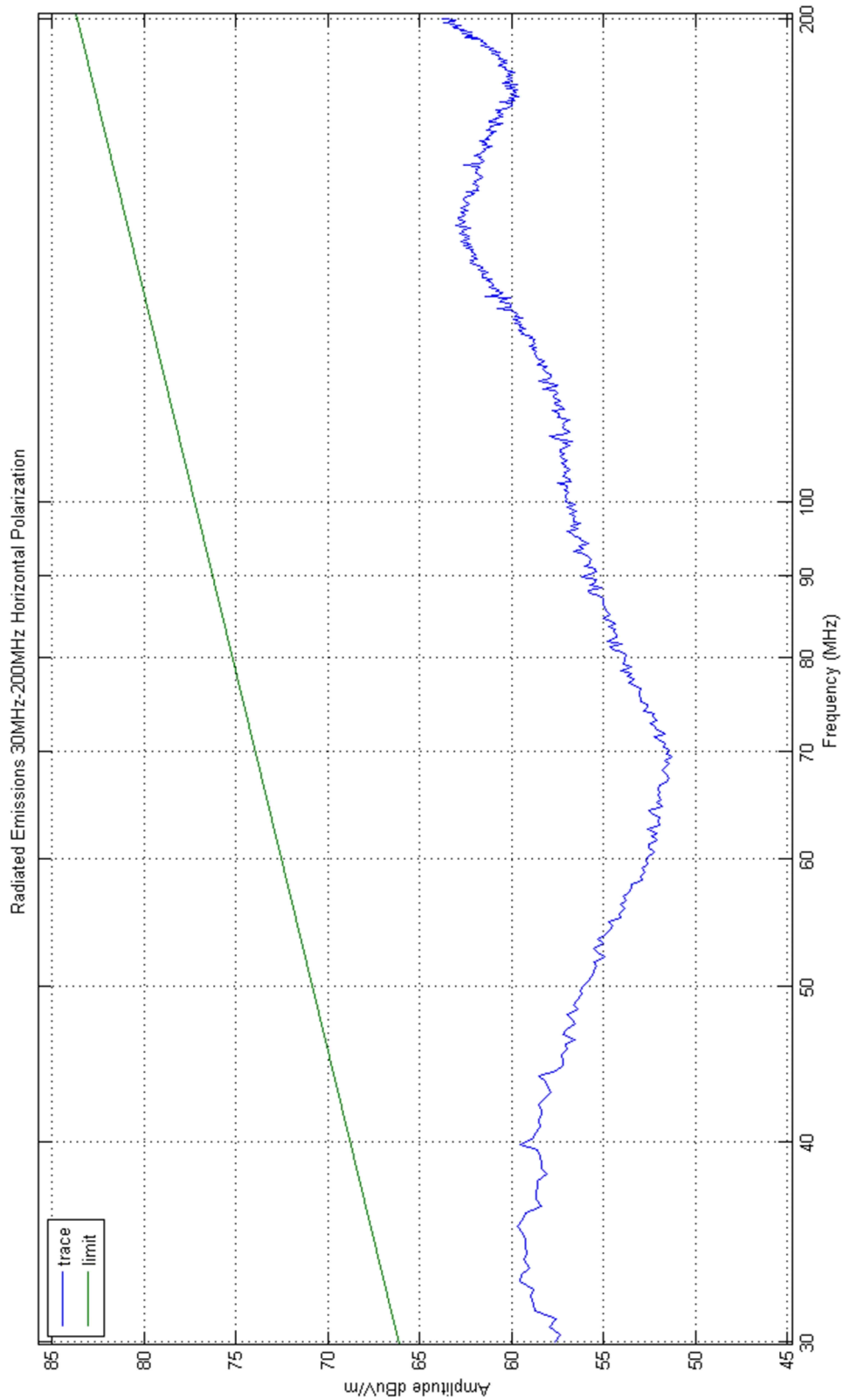


Fig. 39a

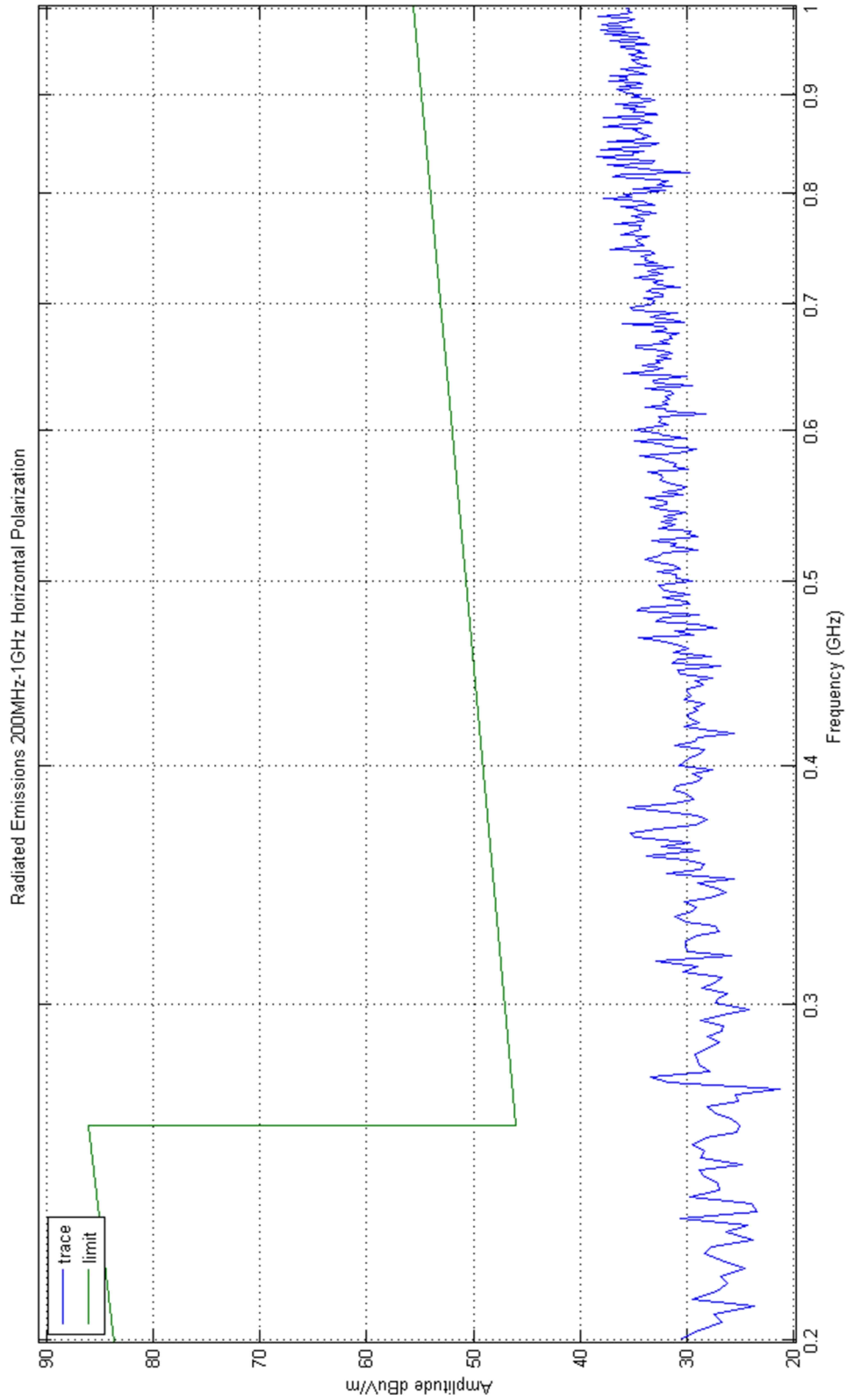


Fig. 39b

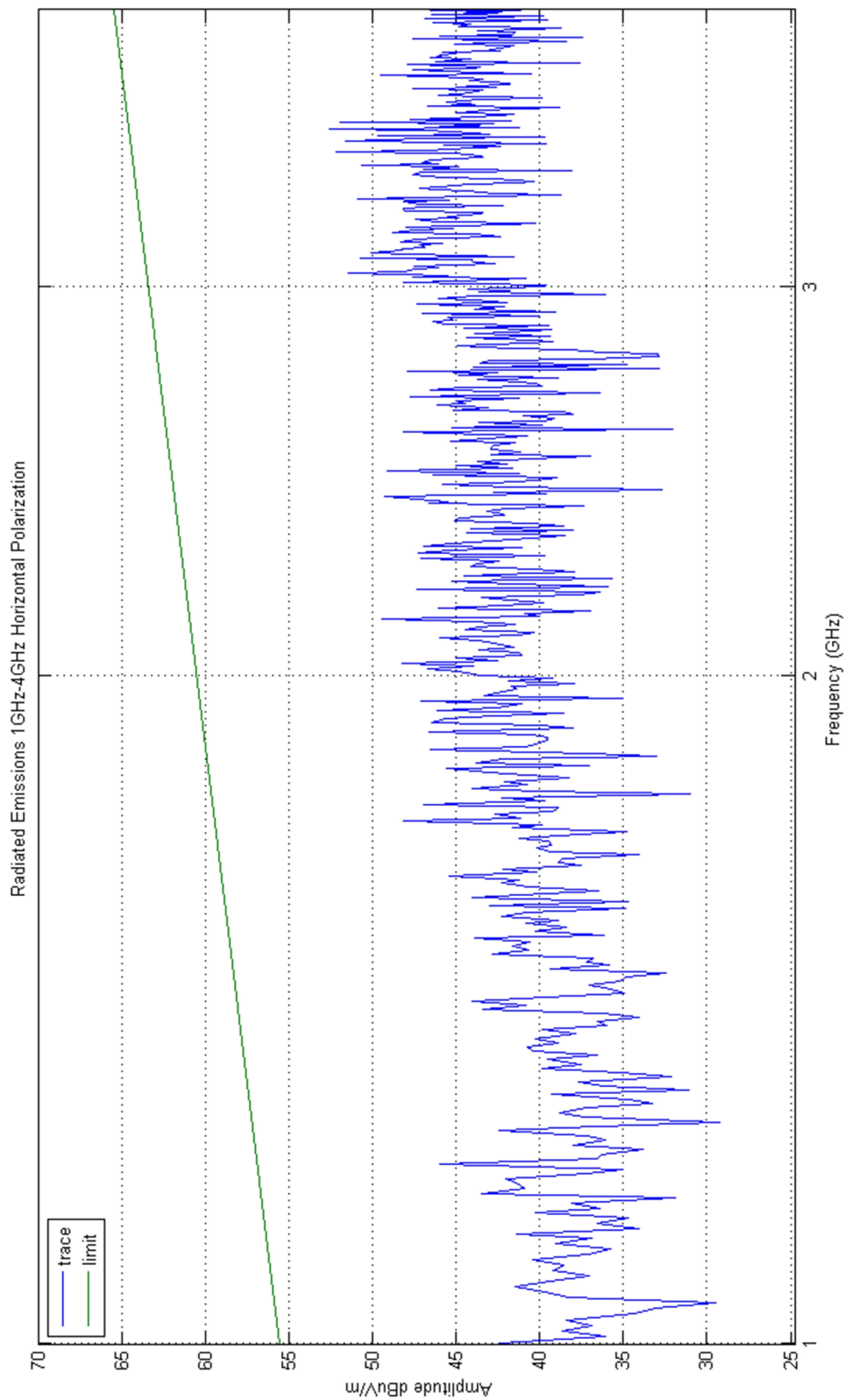


Fig. 39c

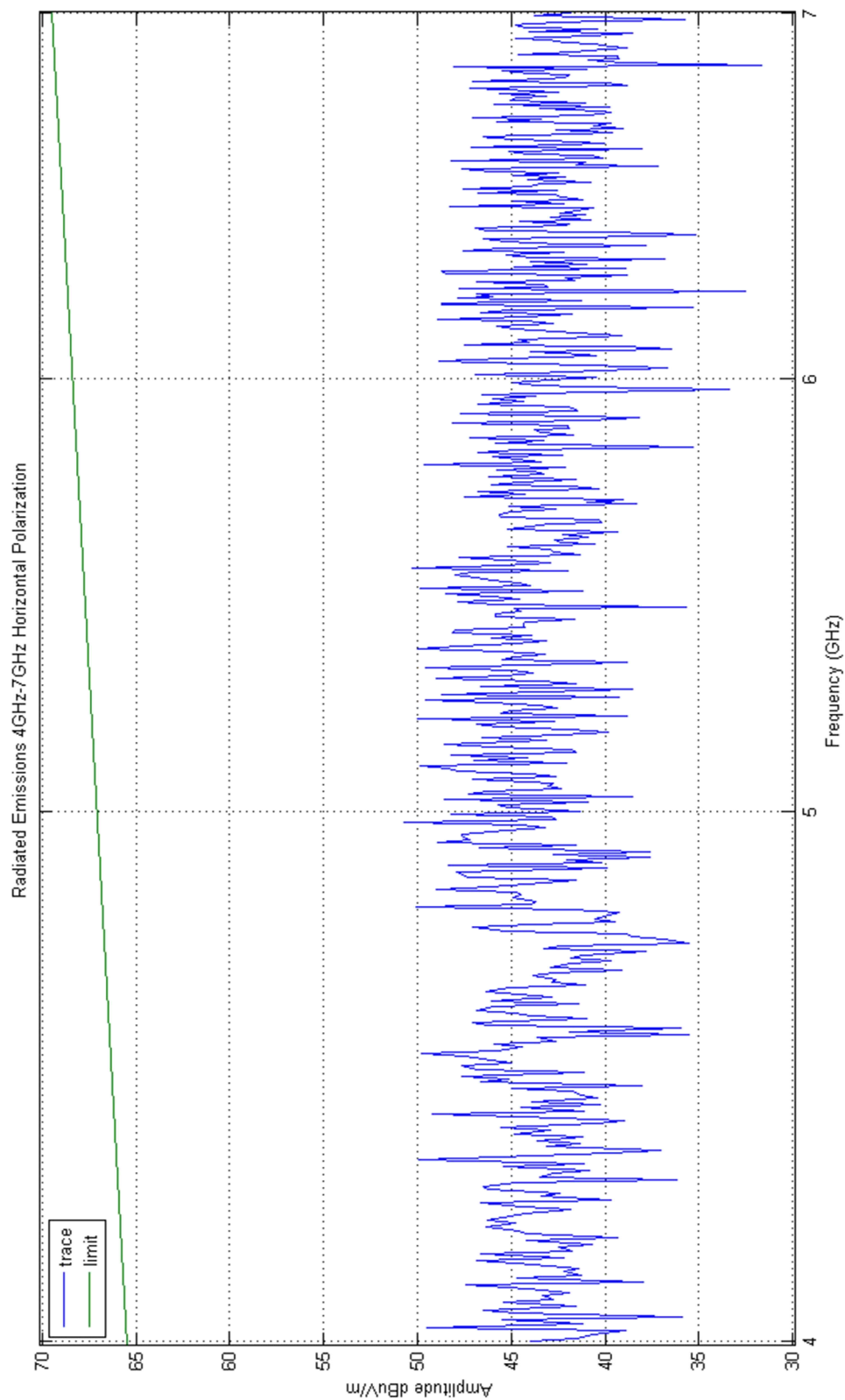


Fig. 39d

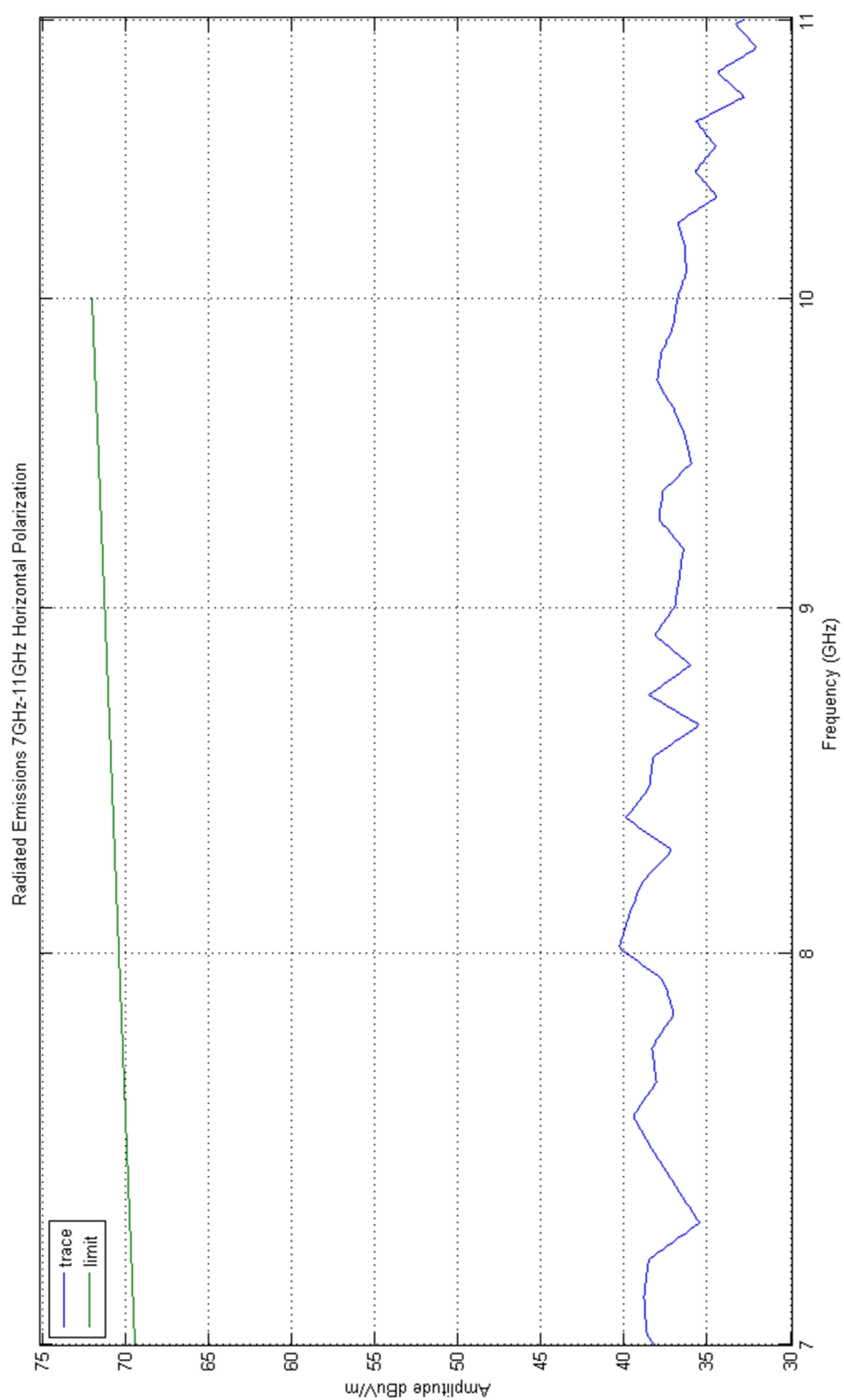


Fig. 39e

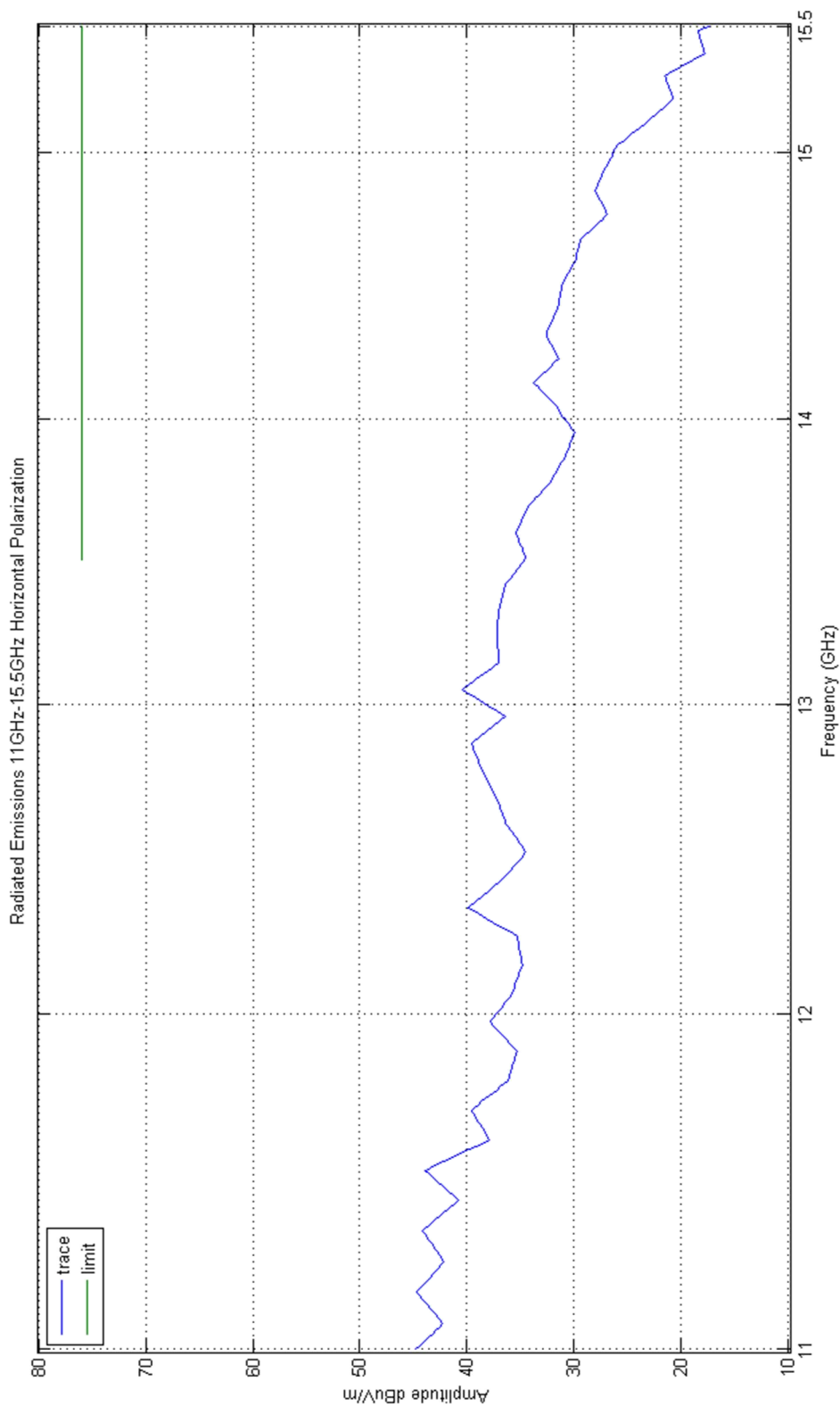


Fig. 39f

Figs. 40(a)-(f) show the radiated emissions measured for the HV Box hot part for frequencies > 30 MHz, with antenna directed vertically. Applicable RE02 limit is also shown for comparison.

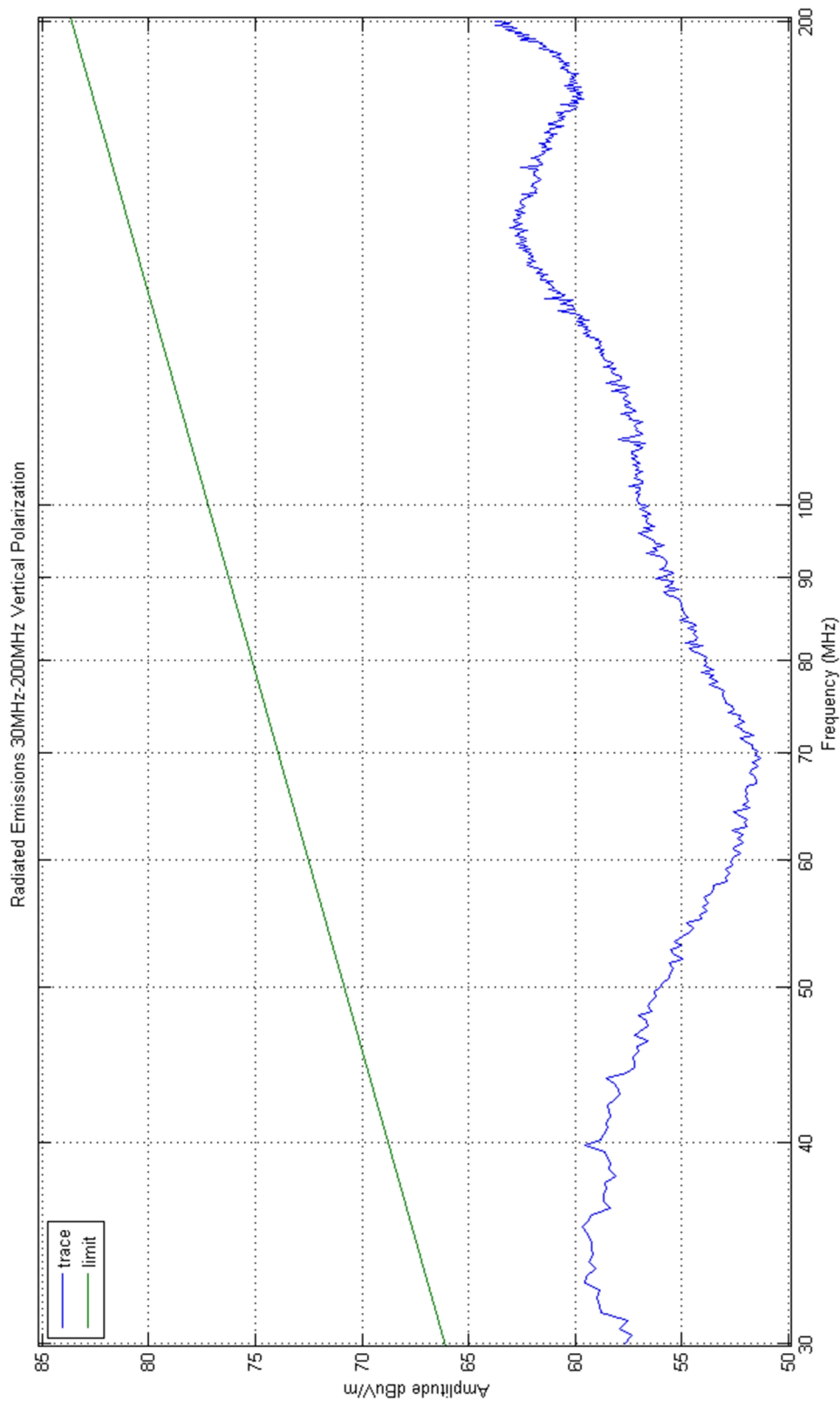


Fig. 40a

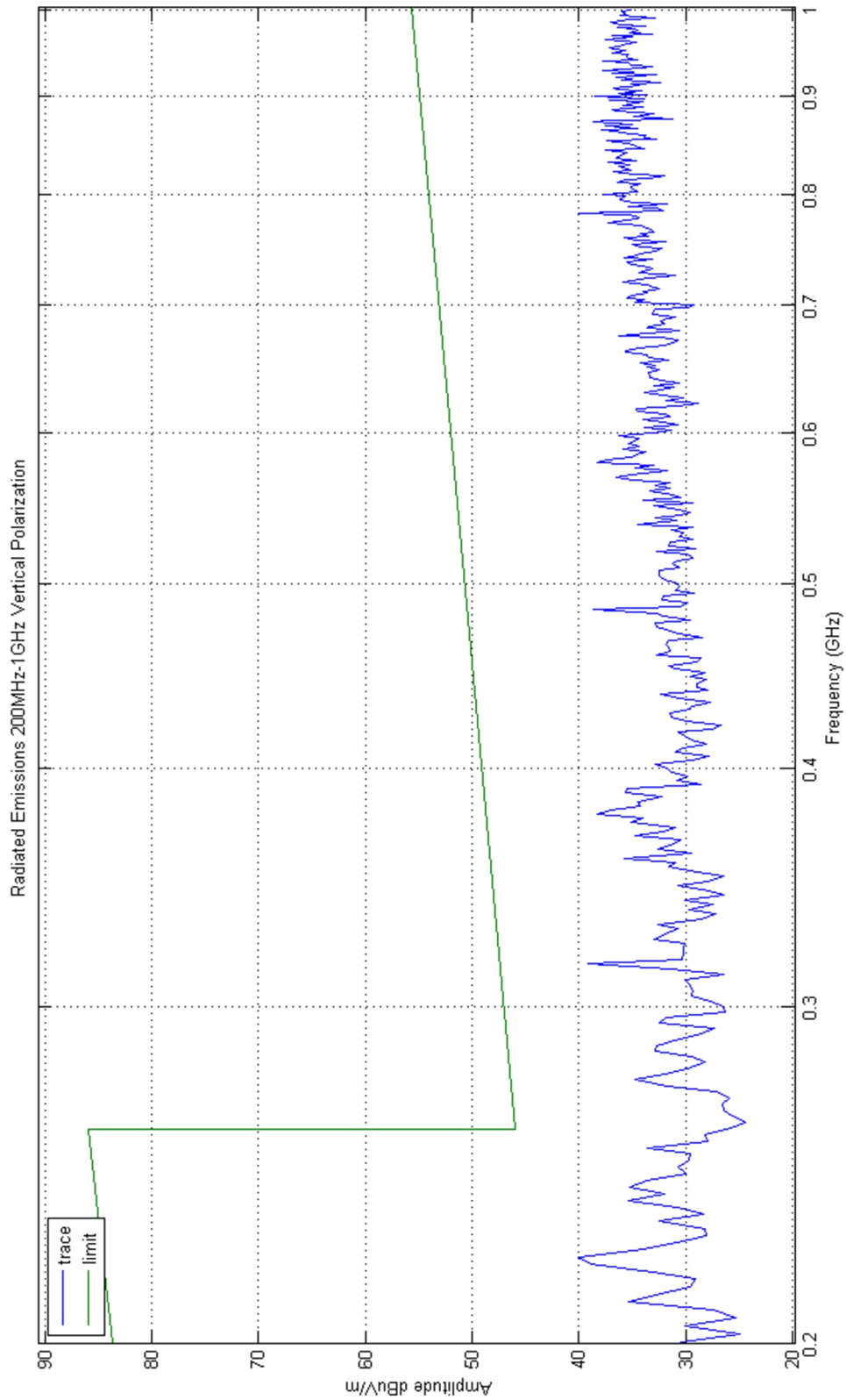


Fig. 406

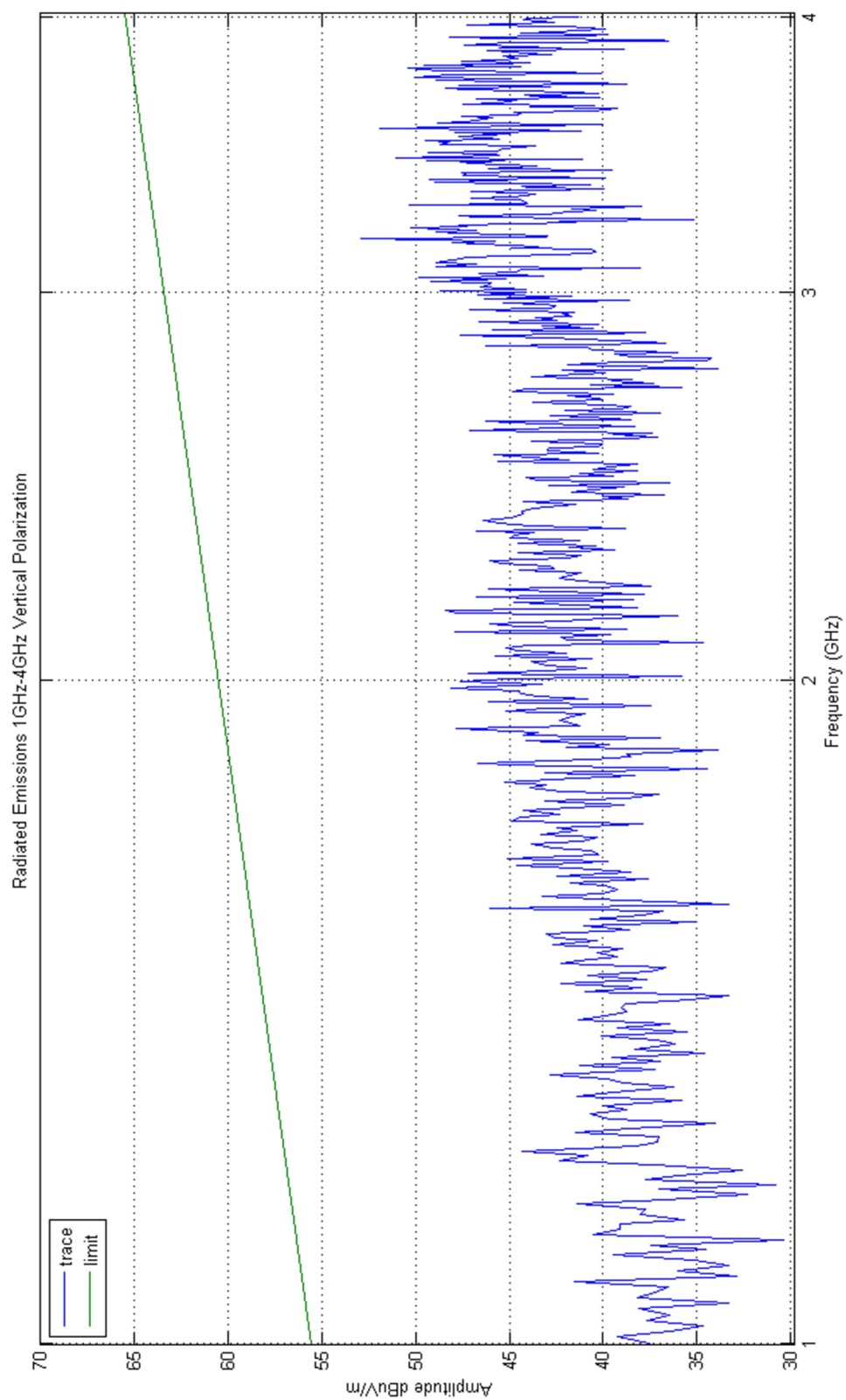


Fig. 40c

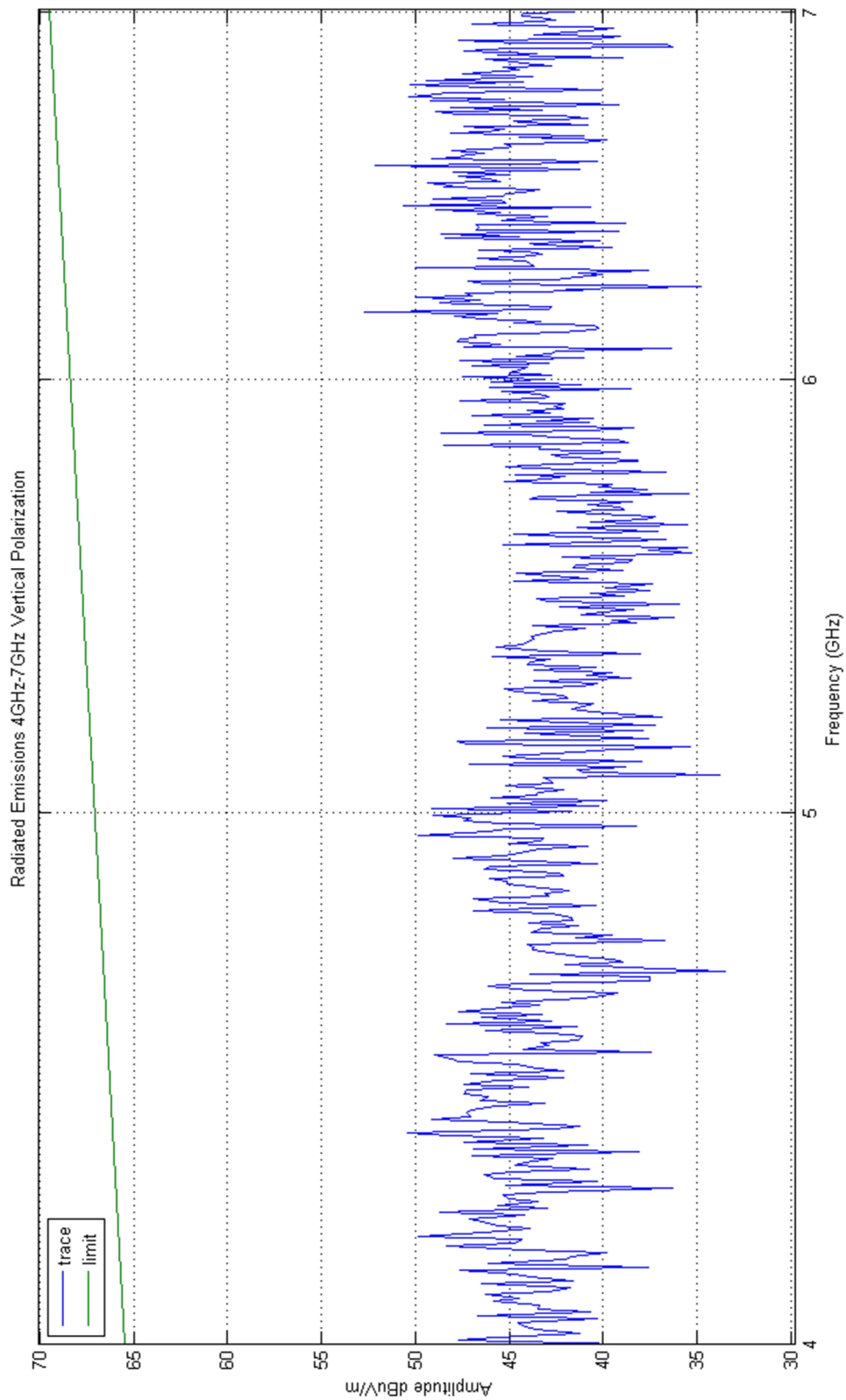


Fig. 40d

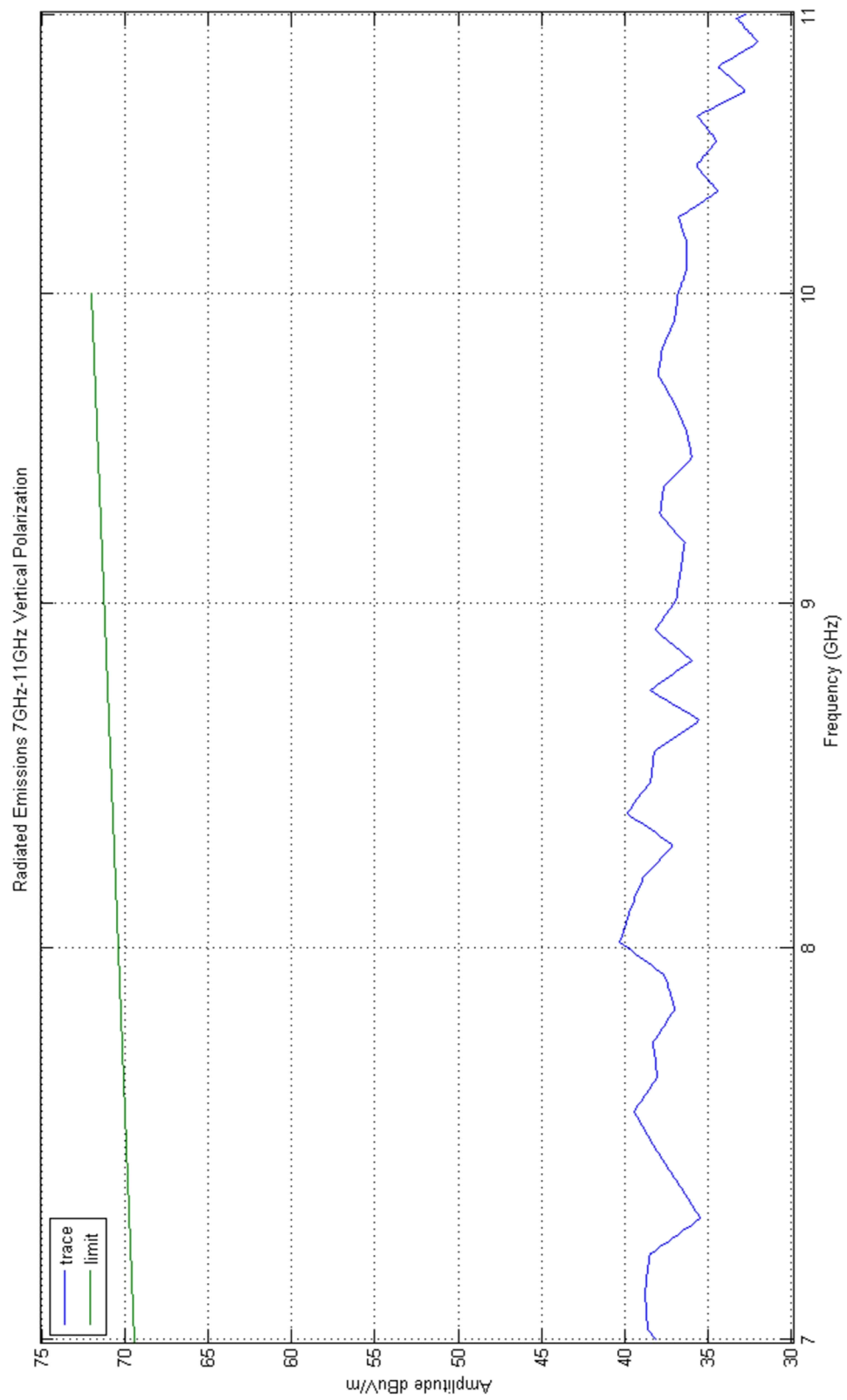


Fig. 40e

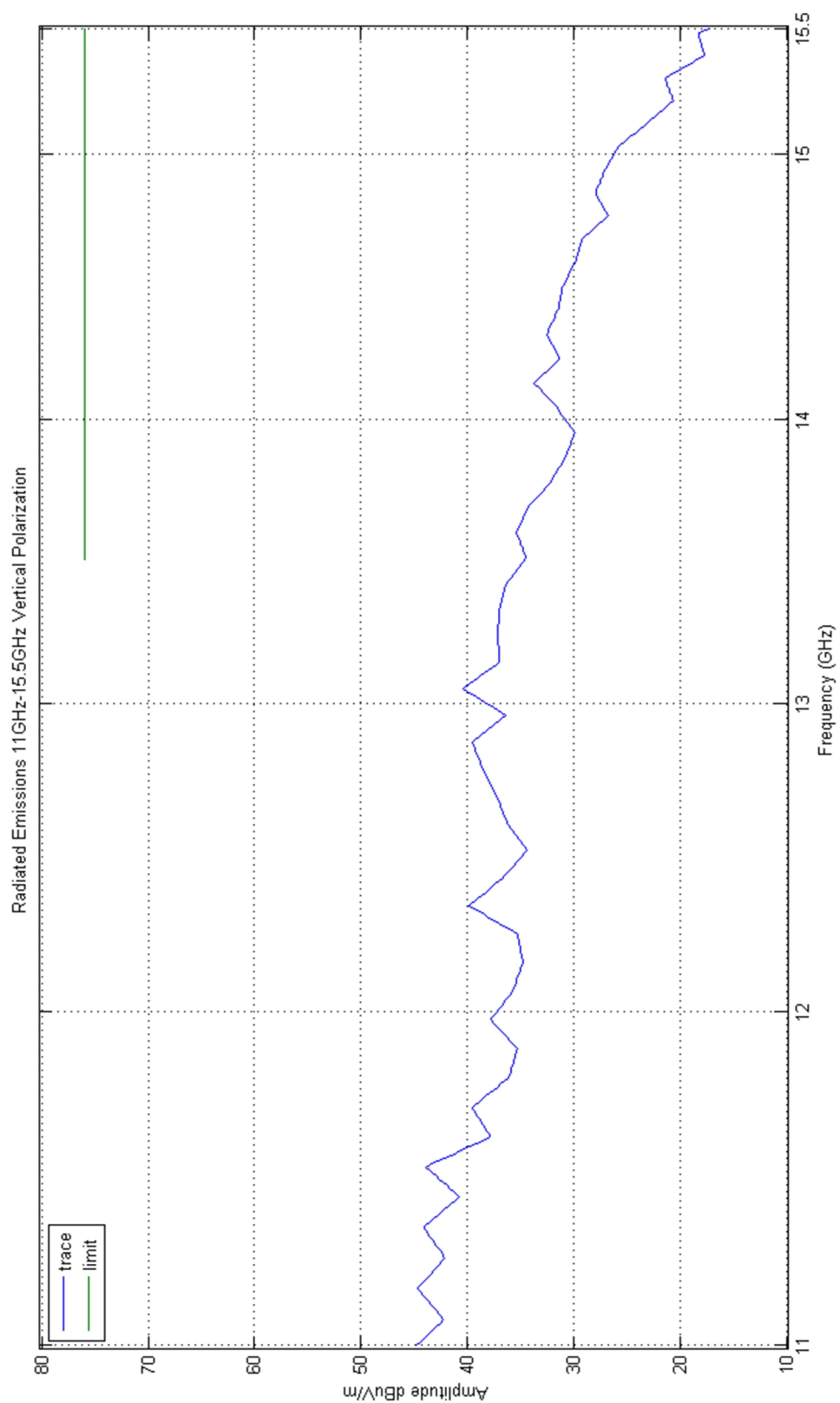


Fig. 40f

8. RS02 test

8.1. Configuration (RS02 test)

The configuration implemented for this test is shown in Fig. 41. The test is performed on the bundle of wires for digital lines. The bundle of wire under test is stressed by taping an insulated AWG12 (or larger) size wire (coupling wire), parallel to the bundle, running the entire length of the bundle to 15 cm from each end connector; the portions of the coupling wire not taped to the bundle are kept well removed from it, in order to couple the maximum flux into the bundle.

During the test, each of four different spike signals (see Tab. 11 and Fig. 42) is repeatedly applied by the spike generator across a non-inductive $10\ \Omega$ resistor, with a repetition rate of 400 Hz each, while a continuous functional/electrical test is performed at least for 2 minutes per spike. Before and after the different spikes are applied, other functional/electrical tests are performed.

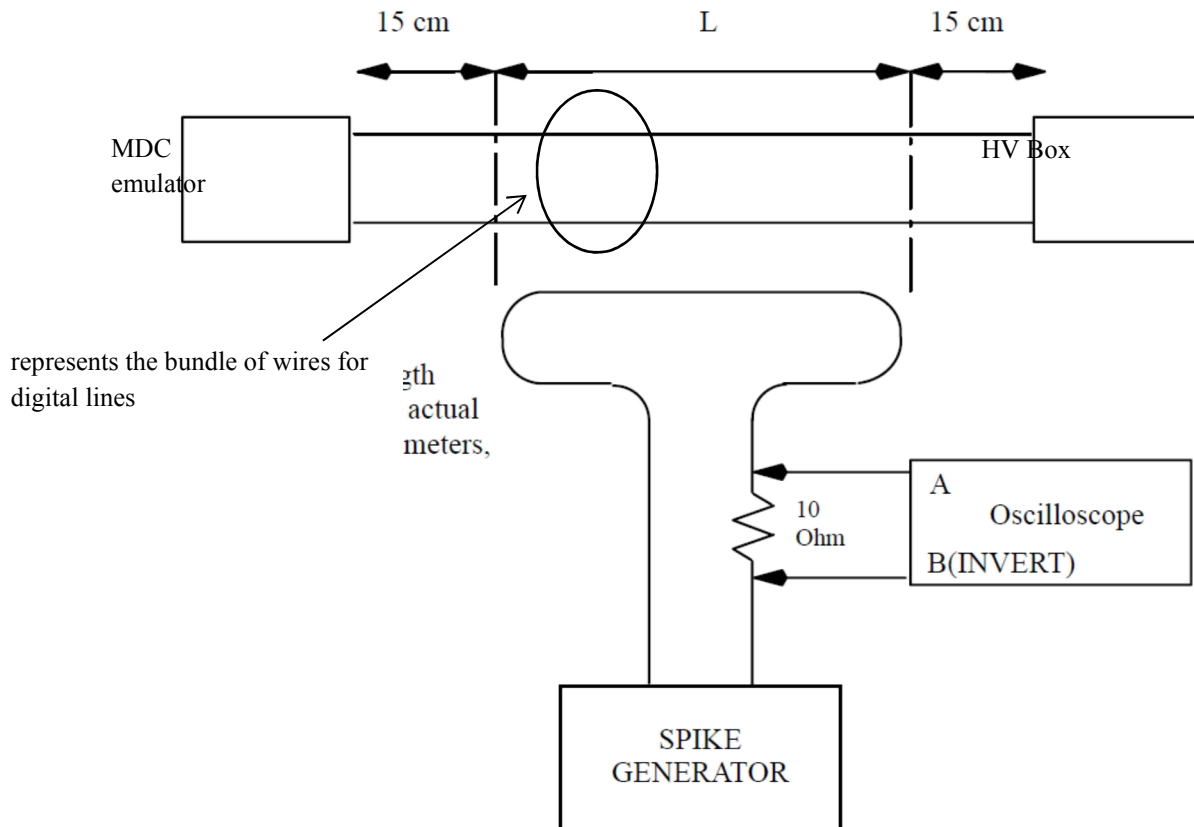


Fig. 41: test set-up configuration for RS02 test. $L = 1.5\text{ m}$.

The waveforms of the spike signals are checked by means of the oscilloscope, reading differentially across the $10\ \Omega$ resistor. The applied spike waveform and repetition rate are recorded.

No susceptibility is found in the apparatus for the bundle under test, if the functional/electrical test is fully passed. Thresholds of susceptibility are determined and recorded where susceptibility is noted; the threshold of susceptibility is specified as follows.

First, the spike amplitude is diminished until the threshold is reached; the corresponding spike amplitude is recorded. Secondly, the spike amplitude is reestablished, and the coupling wire is moved apart from the bundle under

test, to determine the threshold of susceptibility for the separation of coupling wire and bundle. The repetition rate of the functional/electrical anomaly found is also recorded, if applicable.

Tab. 11: amplitude and pulse-width of injected spikes for RS02 test.

SPIKE A	amplitude E (V)	240
	pulse-width t (μ s)	10 ± 2
SPIKE B	same as A, with opposite polarity	
SPIKE C	amplitude E (V)	240
	pulse-width t (μ s)	0.15 ± 0.03
SPIKE D	same as C, with opposite polarity	

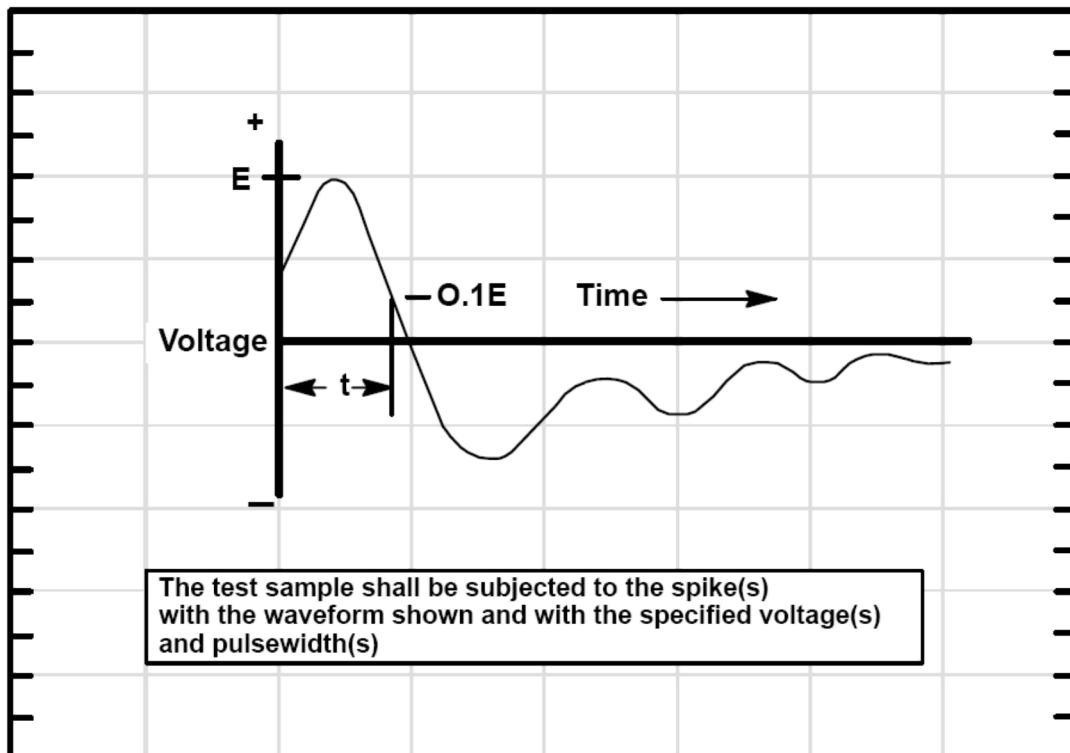


Fig. 42: injected spike waveform for RS02 test.

Employed equipment is listed below.

- Signal generator: custom-made board IFAC-CALET-RS02.
- Oscilloscope (signal monitor): Lecroy 6100A (4 channels). S.N. LCRY0604P16335. Calibration expiry date: 2013-07-12.
- Power supplies, current meters:
 - Agilent U8032A. S/N MY52180017. Calibration expiry date 2013-05-03.
 - TTI QL355T. S.N. 346658. Current meter cross-calibrated with Agilent U8032A.
- Oscilloscope: Agilent DSO6054A (4 channels). S.N. MY44006050. Cross-calibrated with Lecroy Waverunner 6100A oscilloscope.

9. RS03 test

9.1. Configuration (RS03 test)

The configuration implemented for this test is shown in Fig. 43. No parts of the antennas are located at less than 30 cm from the floor and ceiling and at less than 1 meter from the walls of the chamber.

Tab. 12, Tab. 13 and Fig. 44 describe the radiated electric field injection spectrum to be applied at the mounting location of the HV Box. Above 30 MHz, linearly polarized test antennas are positioned so as to generate vertical and horizontal fields. The applied maximum sweep speed for each frequency interval is also specified in Tab. 12.

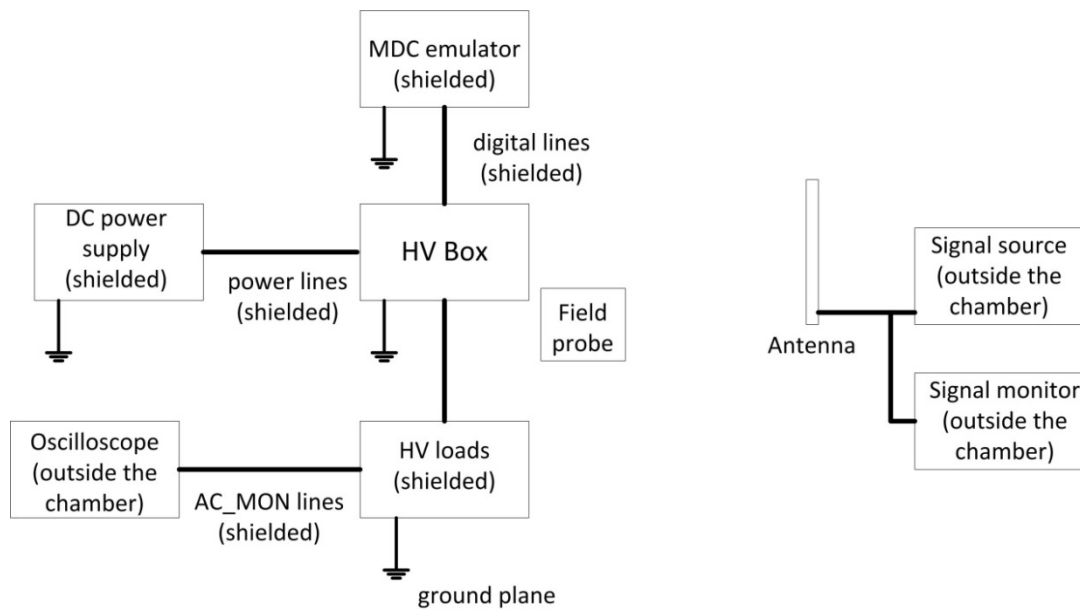


Fig. 43: test set-up configuration for RS03 test.

The specified field intensity is established prior to the actual testing by placing a field measuring antenna at the same distance and in the exact location that the HV Box will occupy and by adjusting the signal level applied to the transmitting antenna until the required field intensity is indicated. During this operation, the transmitting antenna is placed at a distance sufficient to allow the entire volume of the HV Box to fall within the 3 dB beam-width of the transmitted field. If this is not feasible because of either difficulty in generating the required field at the greater distance or the nature of the antenna radiation characteristics, then the HV Box is tested in segments, where each segment is equal in dimension to the 6 dB beam-width of the antenna radiation characteristic. The voltage or power at the input terminals of the transmitting antenna required to establish the specified field is monitored and recorded. In the actual implementation, the HV Box volume fits in the 6 dB beam-width of the antenna radiation characteristic, for the employed antennae.

The specified electric field spectrum is injected while a continuous functional/electrical test is performed. Before and after the frequency sweep, other functional/electrical tests are performed.

No susceptibility is found in the apparatus if the functional/electrical test is fully passed. Otherwise, if susceptibility is found at a given frequency, the input injection level is decreased to determine and record the susceptibility threshold level for the line under test at the given frequency.

Tab. 12: radiated electric field injection spectrum for RS03 test (sweep).

frequency interval		maximum sweep speed (Hz/s)	minimum sweep duration (s)	electric field (V/m, peak)	electric field (V/m, rms)
f_{\min} (Hz)	f_{\max} (Hz)				
14k	20k	0.3k	20	5	3.54
20k	50k	0.6k	50	5	3.54
50k	100k	1.5k	33	5	3.54
100k	200k	3k	33	5	3.54
200k	500k	6k	50	5	3.54
500k	1M	15k	33	5	3.54
1M	2M	30k	33	5	3.54
2M	5M	60k	50	5	3.54
5M	10M	150k	33	5	3.54
10M	30M	300k	67	5	3.54
30M	50M	600k	33	5	3.54
50M	100M	1.5M	33	5	3.54
100M	200M	3M	33	5	3.54
200M	500M	6M	50	60	42.43
500M	1G	15M	33	60	42.43
1G	2G	30M	33	60	42.43
2G	5G	60M	50	60	42.43
5G	8G	150M	20	60	42.43
8G	10G	150M	13	20	14.14

Tab. 13: radiated electric field injection spectrum for RS03 test (stations). All fields are generated with 50% amplitude modulation with 1 kHz sine wave.

frequency	electric field (V/m, peak)	electric field (V/m, rms)
2.2 GHz	161	113.8
8.5 GHz	79	55.86
14.8 GHz - 15.2 GHz	250	176.8

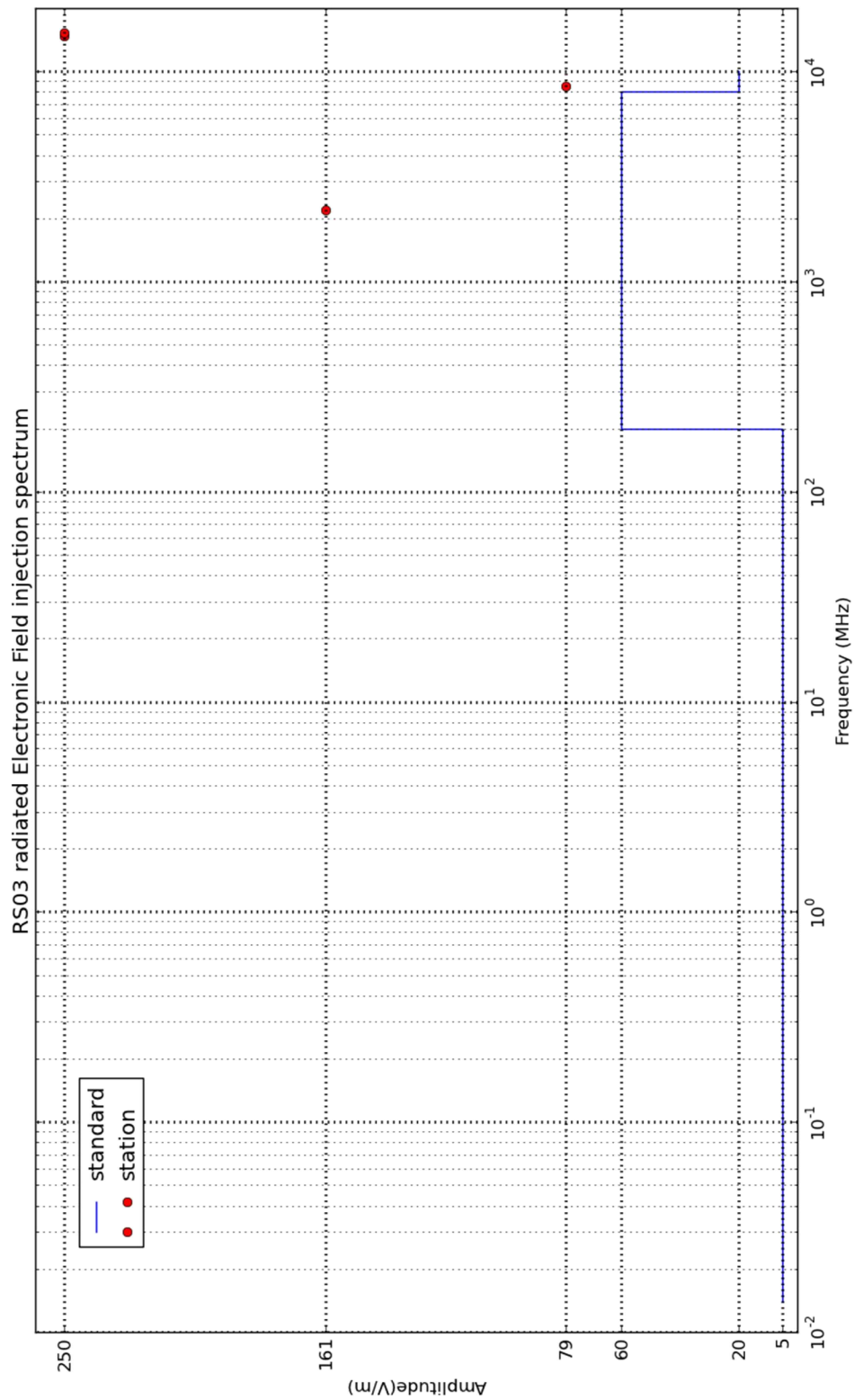


Fig. 44: radiated electric field injection spectrum for RS03 test.

Employed equipment is listed below.

- Signal generators:
 - SG₁. Wavetek 166 pulse/function generator, frequency range 1 mHz - 50 MHz. S.N. T93092032.
 - SG₂. Fluke 6060B synthesized RF signal generator, frequency range 10 kHz – 1.05 GHz. S.N. 3940200.
 - SG₃. Wiltron 68169A synthesized sweep generator, frequency range 10 MHz – 40 GHz. S.N. 202002.
- Signal amplifiers:
 - SA₁. EIN 350L RF power amplifier, frequency range 250 kHz – 105 MHz. S.N. 117.
 - SA₂. 2021 BBS2E4AHM high power RF amplifier, frequency range 20 MHz – 1 GHz. S.N. 1020 D/C 0529.
 - SA₃. MILMEGA AS0825-20L linear power amplifier, frequency range 0.8 GHz – 2.5 GHz. S.N. 1012403.
 - SA₄. KELTEC SR620-20 microwave amplifier, frequency range 2 GHz - 4 GHz. S.N. 92770-632.
 - SA₅. HUGHES 8010H02F000 traveling-wave tube amplifier, frequency range 4 GHz - 8 GHz. S.N. 240.
 - SA₆. LogiMetrics 310/IJ-546 amplifier, frequency range 6 GHz - 18 GHz. S.N. 3177.
 - SA₇. LogiMetrics 610/LS-628 amplifier, frequency range 1 GHz - 2.8 GHz.
 - SA₈. LogiMetrics A600/IJ-682 amplifier, frequency range 8 GHz - 18 GHz.
- Signal monitors:
 - SM₁. Rode&Schwarz ESPI7 EMI test receiver, frequency range 9 kHz - 7 GHz. S.N. 101141. Calibration expiry date: 2013-11-26.
 - SM₂. Tektronix 492AP spectrum analyzer, frequency range 50 kHz - 21 GHz. S.N. B010121. Calibration expiry date: 2012-11-30. Cross-calibrated with Rode&Schwarz ESPI7 EMI test receiver.
- Antennae:
 - AN_{1a}. Custom capacitor antenna, optimized for frequency range 14 kHz - 2 MHz. Two metal grids, square shaped (1 m² area) separated by 1 m vertical distance. The HV Box is placed in the central part of the gap.
 - AN_{1b}. Custom capacitor antenna, optimized for frequency range 2 kHz - 30 MHz. Two metal grids, square shaped (1 m² area) separated by 75 cm vertical distance. The HV Box is placed in the central part of the gap.
 - AN₂. AILTECH 94455-1 biconical antenna.
 - AN₃. Schwarzbeck VUSPL 9111, log-periodical antenna.
 - AN₄. ARA DRG-118/A double ridged-horn antenna.
 - AN_{cal}. ARC PCD8250 biconical antenna.
- Power supplies, current meters:
 - Agilent U8032A. S/N MY52180017. Calibration expiry date 2013-05-03.
 - TTI QL355T. S.N. 346658. Current meter cross-calibrated with Agilent U8032A.
- Oscilloscopes:
 - O₁. Lecroy 6100A (4 channels). S.N. LCRY0604P16335. Calibration expiry date: 2013-07-12.
 - O₂. Agilent DSO6054A (4 channels). S.N. MY44006050. Cross-calibrated with Lecroy Waverunner 6100A oscilloscope.
- Field probes:
 - FP₁. NARDA EHP-50C, frequency range 5 Hz - 100 kHz. S.N. 352WN80533.
 - FP₂. Wandel&Goltermann EMR-300 (meter) and 2244/90.72 (probe), frequency range 100 kHz - 3 GHz. S.N. AM-0074 (meter) and E-0028 (probe).
 - FP₃. RAHAM 484 (meter) and 84C (probe), frequency range 300 MHz - 18 GHz. S.N. 102144 (meter) and 191630 (probe).

Field probes have been calibrated in the frequency range 80 MHz - 2.5 GHz, by means of a known field generated with antenna AN_{cal} (voltage applied to the antenna has been monitored with SM₁).

Tab. 14 shows the employed combinations of instruments for different frequency ranges (sweep). Tab. 15 shows the employed combinations of instruments for different stations.

Tab. 14: combinations of instruments for RS03 test (sweep).

Frequency range	Signal generator	Signal amplifier	Signal monitor	Antenna	Field probe
14 kHz - 100 kHz	SG ₁	SA ₁	SM ₁	AN _{1a}	FP ₁
100 kHz - 2 MHz	SG ₁	SA ₁	SM ₁	AN _{1a}	FP ₂
2 MHz - 30 MHz	SG ₁	SA ₁	SM ₁	AN _{1b}	FP ₂
30 MHz - 200 MHz	SG ₂	SA ₂	SM ₁	AN ₂	FP ₂
200 MHz - 1 GHz	SG ₂	SA ₂	SM ₁	AN ₃	FP ₂
1 GHz - 2.5 GHz	SG ₃	SA ₃	SM ₁	AN ₄	FP ₃
2.5 GHz - 4 GHz	SG ₃	SA ₄	SM ₁	AN ₄	FP ₃
4 GHz - 8 GHz	SG ₃	SA ₅	SM ₂	AN ₄	FP ₃
8 GHz - 10 GHz	SG ₃	SA ₆	SM ₂	AN ₄	FP ₃

Tab. 15: combinations of instruments for RS03 test (stations).

Frequency	Signal generator	Signal amplifier	Signal monitor	Antenna	Field probe
2.2 GHz	SG ₃	SA ₃	SM ₁	AN ₄	FP ₃
8.5 GHz	SG ₃	SA ₇	SM ₂	AN ₄	FP ₃
14.8 GHz - 15.2 GHz	SG ₃	SA ₈	SM ₂	AN ₄	FP ₃

10. Pictures of employed set-ups

Pictures of employed set-up for the various tests are shown in Fig. 45 and following one.

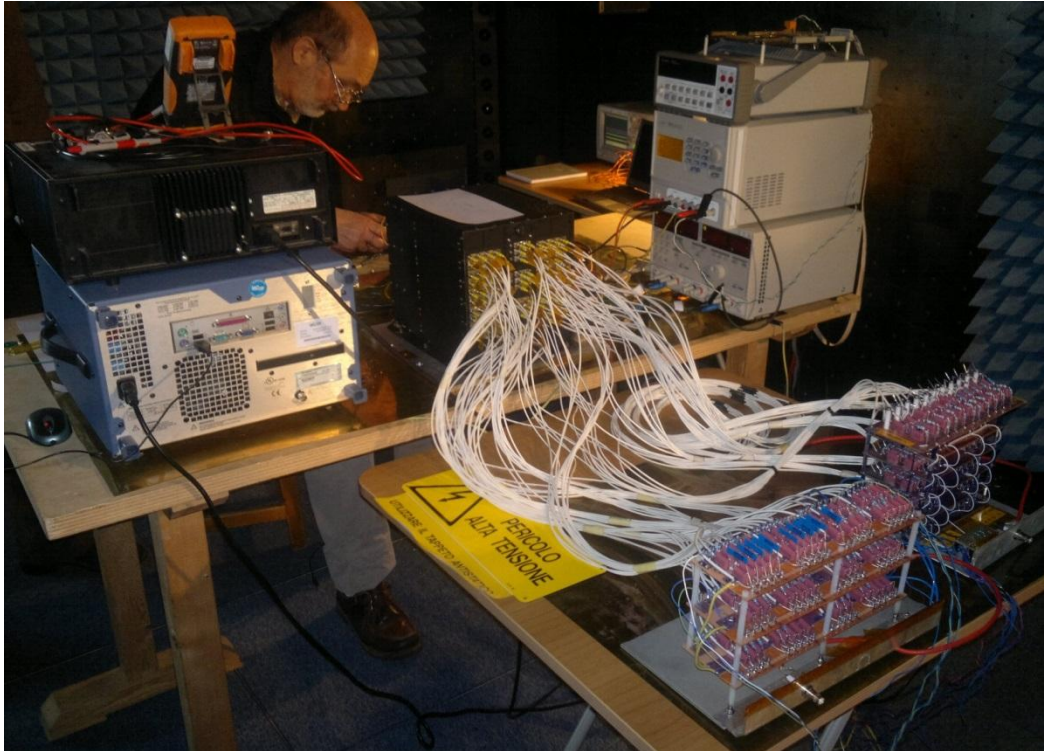


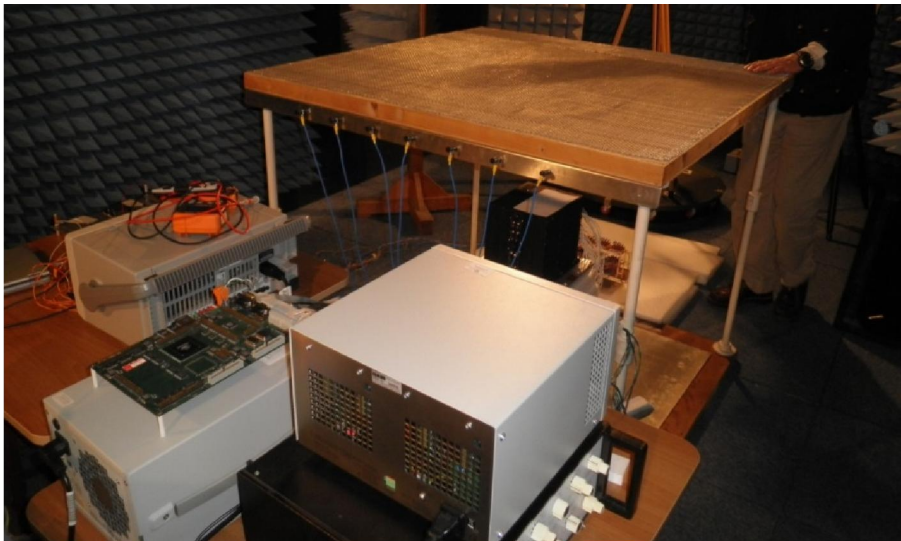
Fig. 45: typical set-up used for conducted tests.



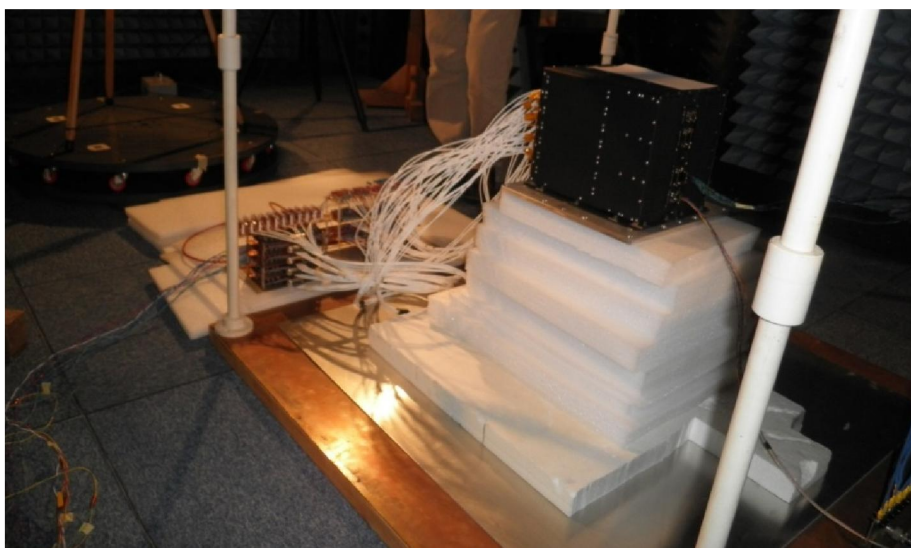
Fig. 46: set-up used for CE07 test.



(a)



(b)



(c)

Fig. 47 (a)-(c): set-up used for CS02 test.

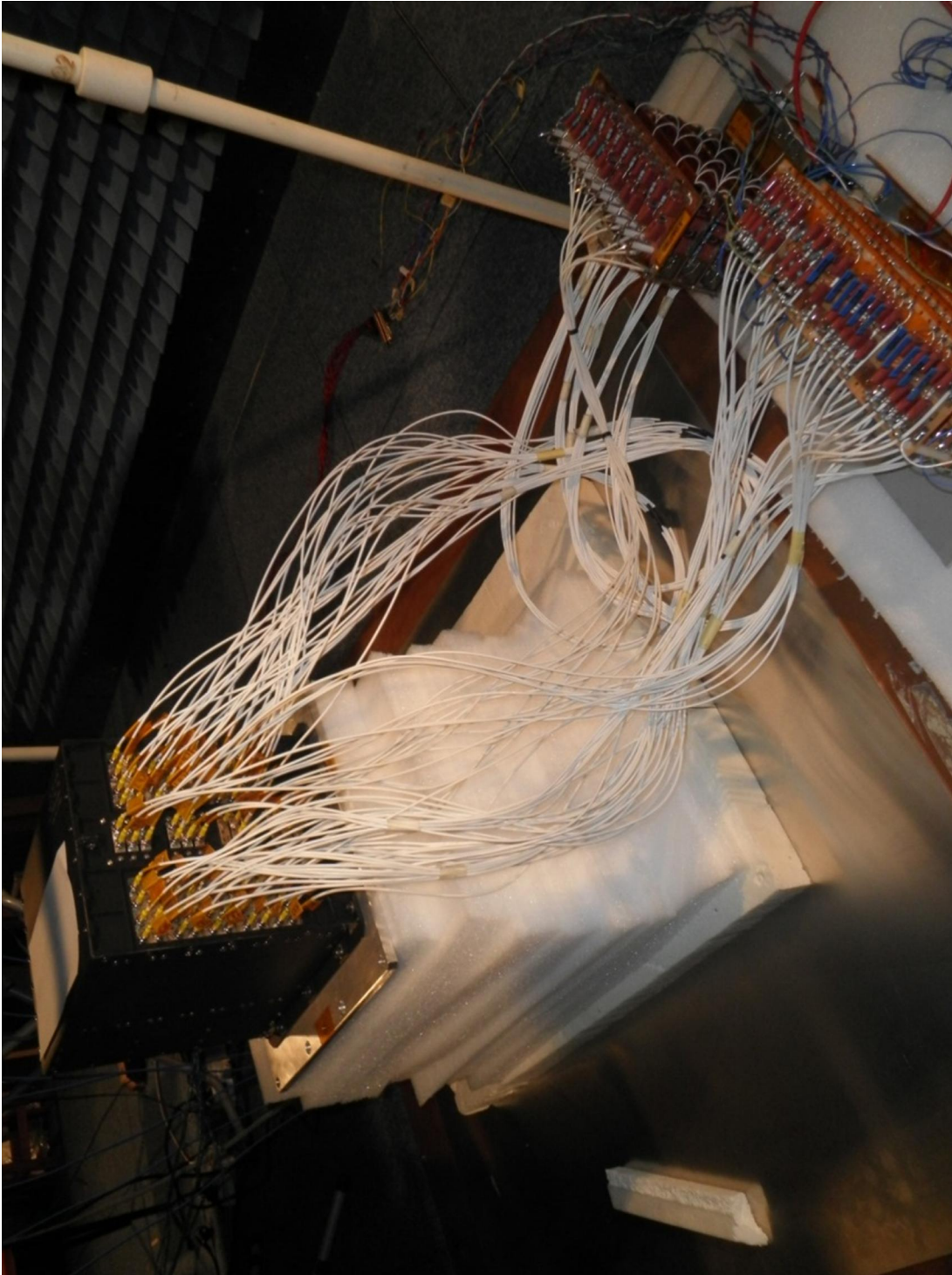
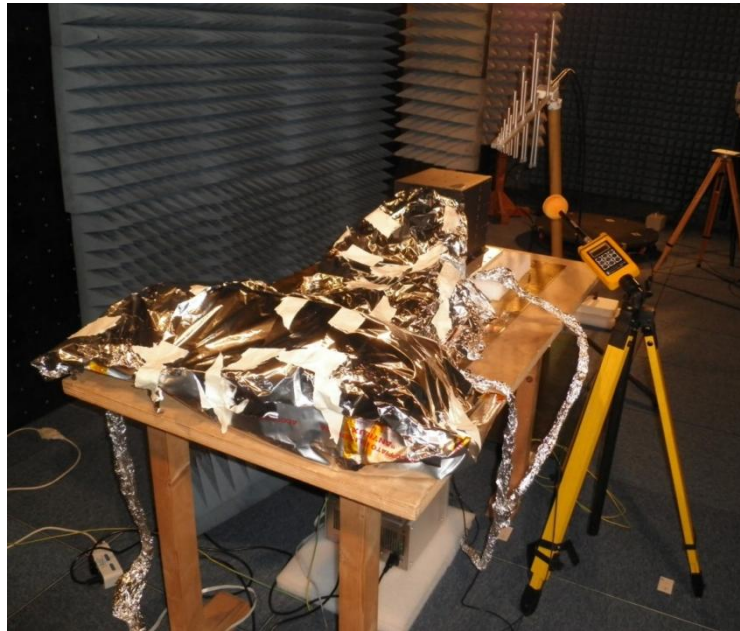
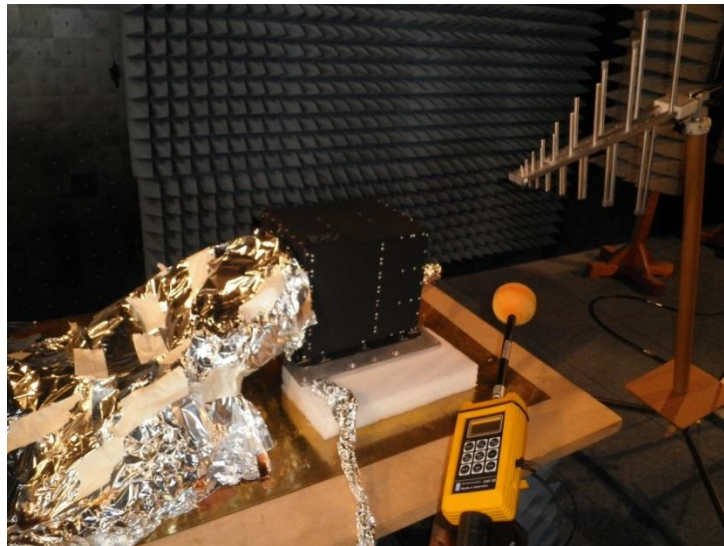


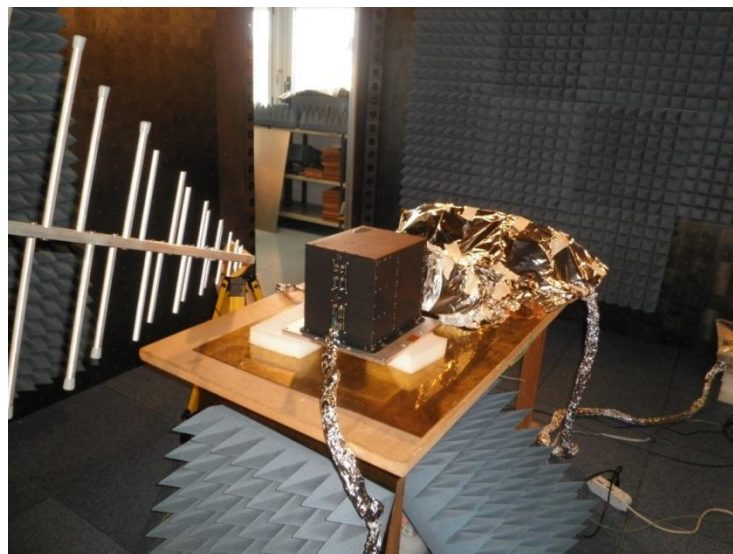
Fig. 48: specific set-up used for RS03 test with custom capacitor antenna.



(a)



(b)



(c)

Fig. 49 (a)-(c): typical set-up used for RS03 test with various antennae.